LICENTIATE THESIS

The Competition for Forest Raw Materials in the Presence of Increased Bioenergy Demand

Partial Equilibrium Analyses of the Swedish Case

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Economics

Luleå University of Technology

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Printed by Luleå University of Technology, Graphic Production 2019

ISSN 1402-1757
ISBN 978-91-7790-298-0 (print)
ISBN 978-91-7790-299-7 (pdf)

Luleå 2019

www.ltu.se




Abstract

Growing energy use and greenhouse gas emissions have implied an increased attention to the development of renewable energy sources. Bioenergy from forest biomass is expected to be one of the cornerstones in reaching renewable energy targets, especially in forest-rich countries such as Sweden. However, forest biomass is a limited resource, and an intensified use of bioenergy could affect roundwood and forest products' markets in several ways. The overall purpose of this thesis is to analyze price formation and resource allocation of forest raw materials in the presence of increased bioenergy demand. The empirical focus is on the competition for wood fibres between bioenergy use and the traditional forest industries, as well as synergy effects between the various sectors using forest raw materials. The methodologic approach is partial equilibrium modeling (forest sector model), and the geographical focus is on Sweden. The thesis comprises three self-contained articles, which all address the above issues.

The first paper presents an economic assessment of two different policies – both implying an increased demand for forest ecosystem services – and how these could affect the competition for forest raw materials. A forest sector trade model is updated to a new base year (2016), and used to analyze the consequences of increased bioenergy use in the heat and power (HP) sector as well as increased forest conservation in Sweden. These overall scenarios are assessed individually and in combination. The results show how various forest raw material-using sectors are affected in terms of price changes and responses in production. A particularly interesting market impact is that bioenergy promotion and forest conservation tend to have opposite effects on forest industry by-product prices. Moreover, combining the two policies mitigates the forest industry by-product price increase compared to the case where only the bioenergy-promoting policy is implemented. In other words, the HP sector is less negatively affected in terms of increased feedstock prices if bioenergy demand target are accompanied by increased forest conservation. This effect is due to increasing pulpwood prices, which reduces pulp, paper and board production, and in turn mitiges the competition for the associated by-products. Overall, the paper illustrates the great complexity of the forest raw material market, and the importance of considering demand and supply responses within and between sectors in energy and forest policy designs.

The second article investigates the forest raw material market effects from introducing second-generation transport biofuel (exemplified by Bio-SNG) production in Sweden. Increases in Bio-SNG demand between 5 and 30 TWh are investigated. The simulation results illustrate increasing forest industry by-product (i.e., sawdust, wood chips and bark) prices, not least in the high-production scenarios (i.e. 20-30 TWh). This suggests that increases in second-generation biofuel productions lead to increased competition for the forest raw materials. The higher feedstock prices make the HP sector less profitable, but very meagre evidence of substitution of fossil fuels for by-products can be found. In this sector, there is instead an increased use of harvesting residues. Fiberboard and particleboard production ceases entirely due to increased input prices. There is also evidence of synergy ("by-product") effects between the sawmill sector and the use of forest raw materials in the HP sector. Higher by-product prices spur sawmills to produce more sawnwood, something that in turn induces forest owners to increase harvest levels. Already in the 5 TWh Bio-SNG scenario, there is an increase in the harvest level, thus suggesting that the by-product effect kicks in from start.

Biofuels and green chemicals are likely to play significant roles in achieving the transition towards a zero-carbon society. However, large-scale biorefineries are not yet cost-competitive with their fossil-fuel counterparts, and it is therefore important to identify biorefinery concepts with high economic performance in order to achieve widespread deployment in the future. For evaluations of early-stage biorefinery concepts, there is a need to consider not only the technical performance and the process costs, but also the performance of the full supply chain and the impact of its implementation in the feedstock and products markets. The third article presents – and argues for – a conceptual interdisciplinary framework that can form the basis for future evaluations of the full supply-chain performance of various novel biorefinery concepts. This framework considers the competition for biomass feedstocks across sectors, and assumes exogenous end-use product demand and various geographical and technical constraints. It can be used to evaluate the impacts of the introduction of various biorefinery concepts in the biomass markets in terms of feedstock allocations and prices. Policy evaluations, taking into account both engineering constraints and market mechanisms, should also be possible.

Overall, the thesis illustrates the importance of considering the market effects when designing and evaluating forest policies and bioenergy policy targets. The forest industry sector and the bioenergy sector are closely interlinked and can both make or break one another depending on the policy design. The results indicate that for an increased demand of bioenergy, an industrial transformation is to be expected, as well as increased roundwood harvest.

Contents

Papers

I. Bryngemark, E. (2019). *Bioenergy versus Biodiversity: A Partial Equilibrium Analysis of the Swedish Forest Raw Materials Market.*

II. Bryngemark, E. (2019*). Second Generation Biofuels and the Competition for Forest Raw Materials: A Partial Equilibrium Analysis of Sweden.*

III. Bryngemark, E., J. Zetterholm, and J. Ahlström (2018). *Techno-economic Market Evaluations of Biorefinery Concepts: An Interdisciplinary Framework.* Under second revision at *Sustainability.*

Acknowledgements

Firstly, I would like to express my sincere gratitude to my main advisor Patrik Söderholm for his continuous support of my work, for always being truly supportive, constructive and sensible, open to possibilities and discussions, and for his generous knowledge sharing of forest markets. I would also like to express my gratitude to my co-advisor Elisabeth Wetterlund for her coaching in pursuing interdisciplinary research, knowledge sharing, positive spirit and support.

During three months in the summer of 2018, I was fortunate enough to be given the opportunity to do research at the International Institute for Applied Systems Analysis (IIASA). I would like to offer my special thanks to Nicklas Forsell and Anu Korosuo at IIASA, not least for enthusiastic encouragement and useful feedback. I would also like to thank Pekka Lauri at IIASA for his generous knowledge sharing in GAMS programing. I would like to express my gratitude to my colleagues at the economics unit at Luleå University of Technology for all the fun and lively discussions during lunches and fikas – I am looking forward to more of that.

This work has been carried out under the auspices of Forskarskolan Energisystem, financed by the Swedish Energy Agency. In Forskarskola Energisystem, I have had the pleasure to get to know and work with wonderful people; a special mention of Jonas Zetterholm and Johan Ahlström, whom I have been fortunate to have as project colleagues.

Finally, I would like to thank my bästisar: Kristina, Malin, and Martin for always reminding me to laugh and enjoy life, for challenging my ideas, and for being there at all times. I would also like to thank the horse Ville for making Mondays such a happy day. Last but not least, I would like to thank my mother Christina and my grandmother Ingrid for continuous encouragement and support in all my pursuits.

Elina Bryngemark, Luleå, January 2019

Preface

1. Introduction

Traditionally, forest biomass has been used to produce forest industry products such as sawnwood and paper. Following an increasing interest for renewable energy and energy security in the 1970s, the use of forest based biomass for energy purposes has increased significantly, not the least in countries with abundant forest resources (e.g. Sweden, Finland and Canada). In Sweden, 26% of total primary energy supply stem from biomass, and out of this 70% originates from forest biomass. Sweden is the largest renewable derived heat generating nation due to its high use of biomass in the heat and power (HP) sector, primarily for district heating purposes (WEA, 2017). There are strong political incentives in the European Union (EU) to increase the share of bioenergy in the energy supply mix further (e.g. EC, 2012b). So-called second generation (2G) biofuels produced from harvesting residues and forest industry by-products are considered sustainable feedstock and believed to be one of the cornerstones in the transition towards a fossil free transport fleet, not the least where electricity may not be entirely feasible, such as in the heavy road transport sector and in the air fleet (EU 10308/18, 2018).

In addition to providing feedstocks to forest industries and bioenergy sectors, forests inhabit many non-monetary values and functions, such as the provision of biodiversity and carbon storage. During the past two decades, a growing recognition that biodiversity is crucial for global well-being have led to more stringent policies aiming to protect forests, e.g. the EU biodiversity strategy to 2020 (EC, 2011). Figure 1 provides an overview of the economic value of forests, some of which are captured in existing markets (e.g. roundwood) while others are not (e.g. ecosystem services).

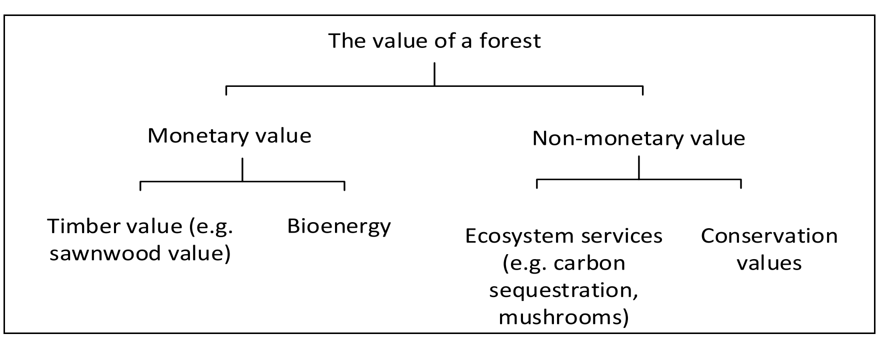

Figure 1: The various economic values of forests

Since market and non-market uses are competing for the same resource, i.e., the forest, the market is unable to solve this allocation problem on its own. For this reason, policies are adopted to correct for various market failures, such as the absence of pricing of public goods provided by the forests. The EU has adopted policies for several areas including increased HP bioenergy, 2G biofuels, and forest conservation to promote biodiversity (EC, 2011, 2012a, c; EU 10308/18, 2018; EU, 2005). But not everyone is satisfied. Söderberg and Eckerberg (2013) observe a rising conflict throughout Europe regarding the allocation of forest resources. These conflicts and the policies have brought academics' attention to the topic, and a significant amount of research, including supply chains evaluations, life-cycle and biological assements, have been carried out (e.g. Bouget et al., 2012; Cherubini et al., 2009; Shabani et al., 2013). Still, the market effects remain less studied, also in the case of Sweden – a country with large forest resources, a well-developed HP bioenergy sector, and considered to be a suitable location for future 2G biofuel production (Mustapha et al., 2017). Meanwhile, Sweden's forest management strategy has tended to develop into a so-called "more-of-everything" strategy, in which policies are continously added (Lindahl et al., 2017). This has spurred an intense national public debate regarding the forest's values and uses (see e.g. DI, 2018; SvD, 2018).

The overall objective of the thesis is to analyze price formation and resource allocation of forest raw materials in the presence of increased bioenergy demand. For policy makers to be able to navigate and understand the implications of one or the other policy, it is essential to understand how future policies could affect the forest raw material markets given the complex web of sectors demanding and supplying forest raw materials. The two first papers in this thesis investigate the market effects from implementing three policies in the Swedish forest raw material market by using (and updating and extending), a so called partial equilibrium forest sector model. In the thesis, we also investigate the possibilities to soft-link this kind of economic modeling approach with two techno-economic models in order to evaluate various new biorefinery concepts. The paper presents an analytical framework that should be able to address the market impacts under different supply chain configurations in an iterative process.

2. The forest raw material market: conceptual issues

In Sweden, the HP sector using bioenergy and the forest industries are closely interlinked via the market for forest raw materials. Both sectors compete for forest raw materials, but they are also interconnected via trade synergies. Sawmills are (direct) suppliers of by-products (e.g. sawdust) and (indirect) suppliers of harvesting residues. These feedstocks can be used as input in the HP sector. However, by-products can also be used in the pulp and paper industries, something which causes feedstock competition. Figure 2 shows a schematic illustration of the interlinkages between the two sectors. The final consumer goods produced in each sector sectors are indicated with downward pointing arrows. The 2G biofuel box is dashed to indicate that production is not yet in commercial scale.

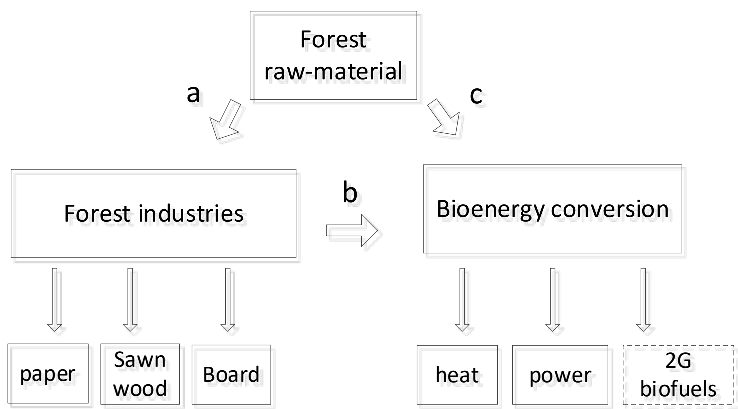

Figure 2: A schematic picture of the demand for forest raw materials, which constitute feedstock two forest industries and the bioenergy conversion sector.

In Figure 2, arrow "a" represents the flow of sawlogs and pulpwood to the forest industries that produce for instance paper, sawnwood, and board products. The forest industries supply by-products, such as sawdust, which can be either used as input in the pellets industry (part of "forest industries") or as feedstock in bioenergy conversion, indicated with the arrow "b". Arrow "c" represents the flow of forest raw material from the forest owners to bioenergy conversion, which theoretically can be both roundwood and harvesting residues, but it is in practice limited to harvesting residues due to relative price differences and not the least to EU's waste hierarchy Directive (2008/98/EC). This hierarchy states that bioenergy produced from roundwood is not categorized as renewable energy since it is deemed to be used more efficiently in other sectors.

The price formation of roundwood is dependent on the total supply of domestic roundwood, domestic harvesting costs, world price for roundwood, and domestic demand for roundwood. The price formation of residuals, i.e., harvesting residues left on the ground after final felling of roundwood, and forest industry by-products (e.g. sawdust from sawnwood production), are different to roundwood since they are produced regardless of the underlying demand for these products. The supply of by-products will therefore be constrained by the main activity, i.e., roundwood harvest and forest industries' main production (e.g. sawnwood). The lowest price for which by-products are supplied is the extraction costs plus the transport costs. The conceptual economics behind supply of harvesting residues and forest industry by-products are similar, here exemplified with harvesting residues in Figure 3. The upper part of Figure 3 includes a supply curve for roundwood and two demand curves for roundwood reflecting two different demand scenarios. The intersection of the roundwood supply and demand curves determines the quantity of roundwood harvested. This sets the limits for the supply of harvesting residues – one for each demand level, which are shown in the lower part of Figure 3.

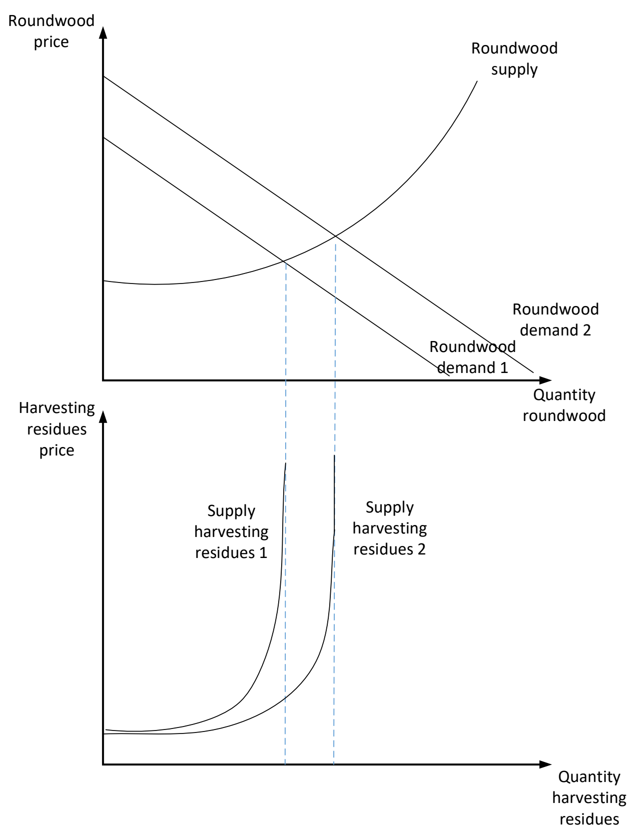

Figure 3: Roundwood supply and demand (upper figure), and harvesting residues supply (lower figure).

A by-product is not expected to influence the level of the main activity (harvest or production) (Söderholm and Lundmark, 2009). Therefore, the marginal cost of harvesting residues is higher the closer it get to its supply limit, and the curve becomes infinitely steep when this limit is reached (lower part of Figure 3). In the case for which a product instead is co-produced with the main product, and thus is required in order to make the main product production profitable, the product is often referred to as a co-product. By definition, the demand for a co-product may influence the production level of the main product (Söderholm and Lundmark, 2009). In this thesis, we acknowledge that under some circumstances high by-product prices may imply that existing by-products turn into co-products.

Figure 4 is a schematic sketch of a forest raw material market with a finite supply of forest raw materials, and two sectors (A and B) competing for the same forest raw material supplied in the market. For example, sector A can be the board industry and sector B the HP sector; both compete for sawdust. If the board industry is alone in the market, quantity qA will be demanded to the price pA. Adding the HP sector to the market creates an (horizontal) aggregated demand curve for sawdust (bold aggregated demand curve). A total amount of sawdust is then supplied to the new higher price P. The existing board sector now has to pay the higher price P for the sawdust.

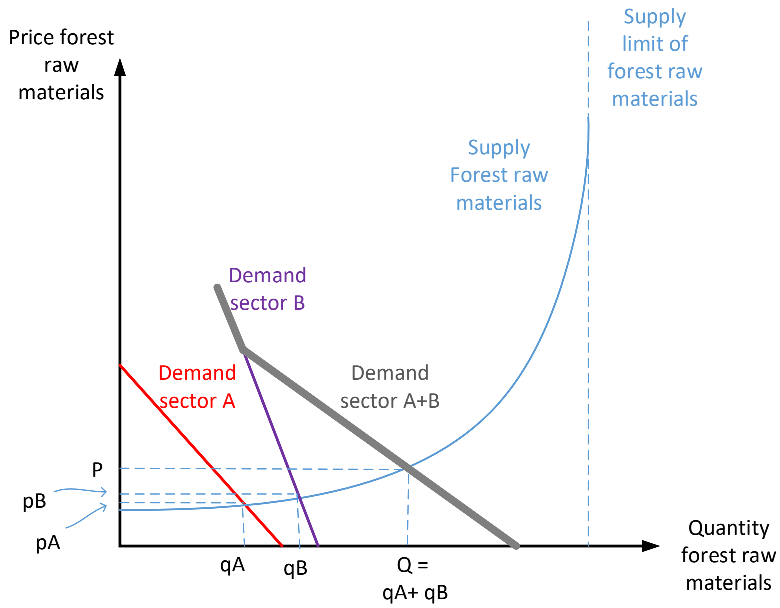

Figure 4: Two sectors competing for the same forest raw materials. Source: Based on Söderholm and Lundmark (2009).

3. Methodology

3.1. Forest sector partial equilibrium modeling

Simulation models are suitable tools for handling complex systems, and for investigating how such systems would react in the presence of, say, a certain policy intervention. In the early 1950s, pure time-series analysis was (more or less) the only quantitative analysis methodology available to researchers who wished to assess the effects from forest market policies. However, predictions were difficult to perform, and various models often indicated contrary results (Buongiorno, 1996). Since then, considerable progress has been made, theoretically but foremost in modeling. Moreover, in the 1980s, improvements in computer capacity revolutionized the methodological approaches available to researchers, and two types of numerical equilibrium models become popular to assess policy impact: the so-called Computable General Equilibrium (CGE) models that emphasize the links between the forest sector and the macroeconomy (e.g. Binkley et al., 1994; Buongiorno et al., 2014), and the so-called partial equilibrium models that focus on a specific market (and/or a few markets) and reach equilibrium in this specific market independently from the development of prices and quantities in other markets (Latta et al., 2013). For a review of the development of forest sector modeling approaches and their applications to Europe, see Toppinen and Kuuluvainen (2010).

The numerical modeling approach can accommodate complex markets including various intermediate and final products and production technologies; this makes the approach especially suitable for forest market policy assessments. Partial equilibrium, including applications to forestry and forest sectors, are often referred to as Forest Sector Models (FSM) (Buongiorno, 1996; Solberg, 1986). Forests, forest industries and the demand for forest industry products are generally geographically dispersed, and therefore a spatial dimension is usually incorporated into a FSM. Specifically, the spatial dimension is used in the optimization process since most FSM are so called spatial price equilibrium models, and build upon the work by Samuelsson (1952) and Takayama and Judge (1964). These authors showed that if the demand price of a product is equal to the supply price plus the transportation costs, and there is trade between the suppliers and demanders, supply and demand constitute a unique spatial price equilibrium. If there is no trade between a suppliers and demanders, then the supply price plus transportation cost is greater than or equal to the demand price. In this way, the initial allocation of trade is identified via a trade optimization problem. For policy impact assessment in the market, new market equilibrium prices and resource allocation are simulated by maximizing the sum of consumers' and producers' surplus in each region (Samuelsson, 1952; Takayama and Judge, 1964). The FSM approach is suitable for policy analyses since prices and quantities are endogenously determined, and will therefore vary with the policy investigated (Latta et al., 2013). Many previous studies have investigated policy effects in forest markets using FSMs (see e.g. Tromborg et al., 2007; and Tromborg et al., 2008 for an assessments of the Norwegian forest market; Kangas et al., 2011; for the finish forest market, and Havlik et al., 2011; and Lauri et al., 2017 for the world forest market). This family of models originates from the Global Trade Model (GTM) developed at International Institute for Applied Systems Analysis (IIASA) by Kallio (1987), which was further developed to EFI-GTM by Kallio et al. (2004).

3.2. The Swedish Forest Sector Trade Model

The model used in this thesis is the so-called Swedish Forest Sector Trade Model (SFSTM), initially developed by Lestander (2011), and further developed by Carlsson (2011) to SFSTMII. The latter also includes a HP sector in which forest biomass is a key input. In this model, Sweden is divided into four geographical regions. These domestic regions trade raw materials and forest industry products with each other, as well as with a region representing the Rest of the World (ROW). The optimization procedure is according to Samuelsson (1952) and Takayama and Judge (1964), and the theory of spatial equilibrium and welfare (i.e., consumer and producer surplus) optimization.

The objective function in which welfare is optimized in the SFSTM II is presented in Equation 1. A detailed explanation of the objective function, the equations representing forest owners' supply functions of roundwood and harvesting residues, industrial processing capacity cost functions, constraints etc., is provided in detail in Carlsson (2011). Equation 1 shows the objective function, which is the net between the benefits of products and HP consumptions, on the one hand; and, on the other hand, the costs of forest raw materials, fossil fuels and other exogenous inputs, additional industrial processing capacity, and trade. Q and X are consumer products and HP demanded, respectively, H is the harvest of roundwood, R is harvest of harvesting residues. Row three corresponds to the input-output representation of production, row four represents the cost for increased plant capacity in the case of increased production, while the last row represents the transport minimization problem.

$$Max_{O,Q,R,G,H,X,T} \left(\begin{array}{c} \sum_{i,f} \int_0^{Q_{i,f}} p_{i,f}\left(Q_{i,f}\right) dQ_{i,f} + \sum_{i,e} \int_0^{X_{i,e}} p_{i,e}\left(X_{i,e}\right) dX_{i,e} \\ - \sum_{i,w} \int_0^{H_{i,w}} p_{i,w}\left(H_{i,w}\right) dH_{i,w} - \sum_{i,d} \int_0^{R_{i,d}} p_{i,d}\left(R_{i,d}\right) dR_{i,d} \\ - \left(- \sum_{i,l,n} p_n O_{i,l}\, \Gamma_{i,l,n} \right) - \left(- \sum_{i,l,o} p_o O_{i,l}\, \Gamma_{i,l,o} \right) \\ - \left(\sum_{i,l} \sigma \delta_l G_{i,l} \right) \\ - \sum_{i,j,k} T_{i,j,k} min_v \left(M_{k,v} + N_{k,v} \Lambda_{i,j} \right) \end{array} \right)$$

Equation 1: The objective function in the SFSTM II

Decision variables

Equation symbol	Description
Q	Consumer goods (e.g sawnwood, Bio-SNG) demanded
X	HP demanded
H	Roundwood delivered
R	Quantity harvested residues
O	Output of main products
W	Quantity harvested roundwood
G	New industrial production capacity
T	Quantity traded
E	Quantity of energy demanded

Indices

Equation symbol	Description
i	Region
f	Consumer products
e	HP market
w	Roundwood types
d	intermediate products
n	exogenous inputs (e.g. labor, materials, and recycled paper)
l	Quantities of by-products generated from producing one unit of main output from a particular industrial processing activity

Parameters

Equation symbol	Description
Γ	Input-Output coefficients
σ	Annuity factor for additional capacity investments
M	Transportation vehicle loading costs
N	Transportation cost per distance unit
Λ	Distance between trading regions

In the first paper, the model is updated to the new reference year 2016, and it is used to assess the market effects from implementing two policy targets: increased bioenergy in the HP sector and increased forest conservation. In the second paper, SFSTMII is extended with a 2G biofuel module to assess the market impacts from introducing such fuels (represented by so-called Bio-SNG). The third paper places a similar model to SFSTMII into a modeling framework, in which the model is conceptually soft-linked with two techno-economic models. By iterating feedstock prices and 2G biofuel technologies, new biorefinery concepts can be evaluated while considering both feedstock price formation and techno-economic aspects such as optimal biorefinery localization and the performance of conversion technologies.

3.3. Model limitations

Partial equilibrium models, as well as other numerical and econometric models, will be sensitive to changes in assumptions and data (Sjølie et al., 2015). This call for sensitivity analyses of the results as well modeling using different models using the same data in order to reduce uncertainty. Paper I does not include an explicit sensitivity analysis, but many scenarios; which in part represents a test of the model's sensitivity. Paper II includes a sensitivity analysis regarding the assumed import levels. Moreover, the empirical results found in paper I-II are in line with economic theory. Based on this, we found no reason to suspect model irregularities or particular sensitivities.

Moreover, a numerical model may suffer from complexity, and this causes difficulties in interpreting the models' results. Buongiorno (1996) warns for using complex and large forest sector models, and argues that a smaller forest sector model focusing on a delimited area (e.g. a country) is likely to be as accurate as a more complex model. The numerical model used in this thesis is complex in the sense that it represents several industries and sectors. However, the model focuses on one country, and it is fully transparent in its design and follows common practice specifications of supply, demand and technological representation similar to its modeling family (e.g. Kallio, 1987; Solberg, 2011).

4. Summary of papers

This section provides a summary of the three papers included in this thesis. A short discussion of the results and possible future research are presented in section 5.

<u>Paper I:</u> *Bioenergy versus Biodiversity: A Partial Equilibrium Analysis of the Swedish Forest Raw Materials Market*

This paper presents an economic assessment of two different policies – both implying an increased demand for forest ecosystem services – and how these could affect the competition for forest raw materials. SFSTMII is updated to a new base year (2016), and used to analyze the consequences of increased bioenergy use in the heat and power (HP) sector as well as increased forest conservation in Sweden. These overall scenarios are assessed individually and in combination. The results show how various forest raw material-using sectors are affected in terms of price changes and responses in production. A particularly interesting market impact is that bioenergy promotion and forest conservation tend to have opposite effects on forest industry by-product prices. Moreover, combining the two policies mitigates the forest industry by-product price increase compared to the case where only the bioenergy-promoting policy is implemented. In other words, the HP sector is less negatively affected in terms of increased feedstock prices if bioenergy demand targets are accompanied by increased forest conservation. This effect is due to increasing pulpwood prices, which reduces pulp, paper and board production, and in turn mitigates the competition for the associated by-products. Overall, the paper illustrates the great complexity of the forest raw material market, and the importance of considering demand and supply responses within and between sectors in energy and forest policy designs.

Paper II: *Second Generation Biofuels and the Competition for Forest Raw Materials: A Partial Equilibrium Analysis of Sweden*

In order to reach the renewable energy policy targets in the transport sector, biofuels produced from forest raw materials (e.g., harvesting residues) can be cornerstones. Still, these raw materials are currently used as inputs in the HP sector and in the forest industries (pulp and paper plants and sawmills). It is essential to understand how these sectors would be affected by an increased penetration of second generation (2G) biofuels. Sweden is interesting to study due to its well-developed forest industries and mature HP sector involving intense use of forest biomass. The technological experiences and a well-developed infrastructure also make Sweden a suitable country for future 2G biofuel production. This study investigates price development and resource allocation in the Swedish forest raw materials market in the presence of 5-30 TWh of 2G biofuel production. A national partial equilibrium of the forest raw materials markets is extended with a Bio-SNG module to address the impacts of such production.

The simulation results show increasing forest industry by-product (i.e., sawdust, wood chips and bark) prices, not least in the high-production scenarios (20-30 TWh), thus suggesting that the 2G biofuel targets lead to increased competition for the forest raw material. The higher feedstock prices make the HP less profitable, but very meagre evidence of substitution of fossil fuels for by-products is found. In this sector, there is instead an increased use of harvesting residues. Fiberboard and particleboard production ceases entirely due to increased input prices. There is also evidence of synergy effects between the sawmill sector and the use of forest raw materials in the HP sector. Higher by-product prices spur sawmills to produce more sawnwood, something that in turn induces forest owners to increase harvest levels. Already in the 5 TWh Bio-SNG scenario, there is an increase in the harvest level, suggesting that the by-product effect kicks in from start.

Paper III: *Techno-economic Market Evaluations of Biorefinery Concepts: An Interdisciplinary Framework*

The third paper is a concept paper presenting a theoretical framework of how to soft-link, and iterate three numerical modeling approaches: one market model (a model similar to the SFSTMII) and two techno-economic models; one evaluating biomass-to-yield and one supply chain model optimizing biorefinery concept including location and conversion technologies, in order to evaluate new biorefinery concepts.

This analytical framework considers the competition for biomass feedstocks across sectors, and assumes exogenous end-use product demand and a number of geographical and technical constraints. It can be used to evaluate the impacts of the introduction of various biorefinery concepts in the biomass markets in terms of feedstock allocations and prices. Policy evaluations, taking into account both engineering constraints and market mechanisms, should also be possible.

Biofuels and biochemicals are likely to play significant roles in achieving the transition towards a fossil free society. However, large-scale biorefineries are not yet cost-competitive with their fossil-fuel counterparts, and it is important to identify biorefinery concepts with high economic performance in order to achieve widespread deployment in the future. For evaluation of early-stage biorefinery concepts, there is a need to consider not only the technical performance and the process costs, but also the performance of the full supply chain and the impact of its implementation in the feedstock and products markets. This paper presents a conceptual framework to pursuit such holistic evaluation of new biorefinery concepts.

5. Findings, implications and future research

Papers I-II shed light on the market effects from introducing one or more policies affecting the price formation and the resource allocation in a national forest raw material market. None of the policy targets assessed has the purpose to affect the forest raw material market per se, but to obtain a certain level of bioenergy production and/or forest conservation. Nevertheless, in a market characterized by competition for raw materials, changes in price formation and resource allocation cannot be avoided.

In both papers, we observe that the fiberboard and particleboard industries cease their production due to the higher sawdust prices and the competition with the pellets industry. Have we in this way identified that introducing bioenergy targets causes welfare problems? Assuming that the policy targets are correcting for market failures, e.g. negative climate externalities associated with fossil fuels, the answer is no. Structural transformations are not a problem per se according to welfare theory (Söderholm and Lundmark, 2009). Nevertheless, it is important to understand the market consequences from implementing a certain policy in order to evaluate its effects. For instance, a policy design may lead to the shutdown of a by-product provider causing increased feedstock prices, something which in turn leads to substitution from biomass to fossil fuels in the HP sector. That being said, it is not self-evident how to re-design such policy. In order to design efficient policies, policy makers need to be aware of the various market impacts of the policies.

This thesis has demonstrated the importance of market considerations as well as the difficulties to predict the outcome using solely economic reasoning. A model is necessary to simulate a complex market in order to understand price development and resource allocation. There exist, though, several areas for improvements of the SFSTMII in terms of, for instance, time dimension, increased spatial resolution, etc. In order to assess the market impact from policy targets, more details can be added to the analysis, such as different technologies to produce 2G biofuels, plant characteristics, etc. These areas of future research are discussed in more detail in papers I-II. Paper III presents the beginning of a future research path including not only market impacts, but the market in relation to engineering aspects and varios techno-economic constraints.

Moreover, with a changing climate, bioenergy and forest conservation policies may affect the forest raw material markets differently in the future. Wildfires are expected to break out more often and prevail for a longer period of time due to climate change (Boulanger et al., 2017; Flannigan et al., 2009). In the summer of 2018, Sweden experienced a large number of large forest wildfires – the most serious wildfires in Sweden's modern history, according to the Swedish Civil Contingencies Agency. Wildfires (and other natural hazards) are very little understood in the context of policy design in relation to other policies and their market impacts. Verkerk et al. (2018) argue that a paradigm shift is needed – from the current focus on fire suppression to a more holistic policy design in which forest and fire management strategies are integrated, for more efficient use of the forest values (recall Figure 1). Thus, price formation and resource allocation assessments of forest fires scenarios, as well as forest fire policies, could add to the understanding of forest raw material markets, and in turn, consequences for bioenergy and forest conservation.

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Paper I

Bioenergy versus Biodiversity: A Partial Equilibrium Analysis of the Swedish Forest Raw Materials Market

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Abstract

This paper presents an economic assessment of two different policies – both implying an increased demand for forest ecosystem services – and how these could affect the competition for forest raw materials. A forest sector trade model is updated to a new base year (2016), and used to analyze the consequences of increased bioenergy use in the heat and power (HP) sector as well as increased forest conservation in Sweden. These overall scenarios are assessed individually and in combination. The results show how various forest raw material-using sectors are affected in terms of price changes and responses in production. A particularly interesting market impact is that bioenergy promotion and forest conservation tend to have opposite effects on forest industry by-product prices. Moreover, combining the two policies mitigates the forest industry by-product price increase compared to the case where only the bioenergy-promoting policy is implemented. In other words, the HP sector is less negatively affected in terms of increased feedstock prices if bioenergy demand targets are accompanied by increased forest conservation. This effect is due to increasing pulpwood prices, which reduces pulp, paper and board production, and in turn mitigates the competition for the associated by-products. Overall, the paper illustrates the great complexity of the forest raw material market, and the importance of considering demand and supply responses within and between sectors in energy and forest policy designs.

Keywords: bioenergy, biodiversity, partial equilibrium model, forest raw materials; market competition, Sweden

1. Introduction

This paper addresses the question of how two different policies – both implying an increased demand for forest ecosystem services – may affect the competition in terms of price impacts and resource allocation of forest raw materials. The focus is on policies promoting forest conservation (and biodiversity) on the one hand and those inducing an increase in the use of forest-based bioenergy use on the other. It should be clear that implementing these two policies at the same time could involve difficult trade-offs and potential goal conflicts; i.e., an increased ambition for one policy may make it more difficult to pursue the other. Specifically, the costs of increasing the demand for forest-based biofuels will be higher in the presence of more stringent forest conservation policies. In this paper, we investigate the market interactions between the various sectors supplying and relying on forest raw materials in the presence of the two policies. This is achieved in the empirical context of the Swedish forest raw material market.

Goal conflicts exist in all policy areas, not the least in the environmental domain (Geijer et al., 2011; Henkens and van Keulen, 2001; Henle et al., 2008). Due to the many values and biological functions of forests, it should be of no surprise that various policies affecting the use of forest raw materials include contrapositions. Whereas forest bioenergy contributes to reduced greenhouse gas (GHG) emissions from fossil fuels and improved security of energy supply, a standing forest supplies biodiversity, carbon sequestration and other significant ecosystem services. With an increasing global interest for bioenergy as well as a growing recognition that biodiversity is very important for global well-being, the debate about the optimal use of forest resources has intensified, not least in countries where forestry constitute a central part of the domestic economy. Several studies have illuminated this increasingly conflict-ridden policy area (e.g. Kline et al., 2015; Kroger and Raitio, 2017; Wuestemann et al., 2017) and various environmental evaluations of bioenergy in the context of climate change mitigation have been conducted (e.g. Carmenza et al., 2017; Gasparatos et al., 2017). However, the market effects of policy mixes aiming at both forest conservation and the exploitation of biomass for energy generation purposes in terms of raw material price formation and resource allocation, e.g. between the heat and power (HP) sector and the traditional forest industries, have been less studied.

A few studies have addressed such market effects, but typically with a focus on the environmental outcomes and with energy converted from non-forest biomass. Dixon et al. (2013) found that the combination of two EU directives, one promoting bioenergy and the other promoting forest conservation, would lead to increased food prices in economically vulnerable countries due to increased land prices. Geijer et al. (2011) found that increasing forest conservation, according to the Swedish policy *Sustainable Forests*, lead to increased GHG emissions in Sweden due to feedstock substitution from forest biomass to oil in the Swedish HP sector – a result in direct conflict with Sweden's policy *Reduced Climate Impact.* Both of the above studies illustrate the importance of studying feedstock price formation, and its consequences for resource allocation under conflicting polices.

Bioenergy conversion is closely interlinked with forest industries via the market for forest raw materials in which both types of sectors compete for the feedstock. The objective of this paper is to take these interlinkages into account, and investigate forest raw material price formation and resource allocation in a domestic forest biomass market in the presence of increased bioenergy HP demand as well as decreased forest raw material supplies following the implementation of forest conservation policies. The analysis builds on the use of a partial equilibrium model of the Swedish forest raw materials market. In this model, forest owners supply raw materials (e.g. sawlogs), and consumers demand final use products (e.g. sawnwood and energy) (Carlsson, 2011). The forest industries, such as pulp and paper industries and sawmills, and the HP sector demand feedstock, and produce forest products and convert biomass to energy, respectively. The prices for the raw materials, including any by-products (e.g. sawdust, harvesting residues) from the forest industries, will be affected by the underlying demand.

Within this model, three types of scenarios are analyzed: (a) increased demand for forest bioenergy in the HP sector; (b) reduced supply of forest raw materials due to increased forest conservation initiatives; and (c) a combination of (a) and (b). This research focus is motivated for the following reasons: (a) it indicates whether resources tend to be drawn away from the bioenergy-using HP sector under increased forest conservation; (b) it reveals how altered raw material prices affect the forest industries' production patterns; and (c) it gives insights to how by-product supplies are affected and, in turn, how this could influence the allocation of the feedstock across sectors. Unlike the lion share of previous studies, the present study focuses entirely on the market aspects of the underlying goal conflict, in turn permitting an in-depth economic analysis of a disaggregated forest raw material market. Unlike life-cycle or techno-economic models, this study allows for the price formation of biomass feedstocks and products. Changes in prices will lead to altered forest raw material resource allocations between sectors and industries. Such an assessment should be able to shed light on the magnitudes of at least some of the difficult trade-offs in society's use of forest resources, and assist in supporting key decision-making processes in the field.[1]

Sweden is an interesting case to study in the context of conflicting forest policies. With its land area consisting of 57% productive forest land, a well-developed forest industry sector and mature HP bioenergy sector, the country possesses many of the prerequisites for further expanding the use of bioenergy, both in the HP sector and in new fuels for transport (Mustapha et al., 2017a). Such a development is in line with the European Union's ambitious renewable energy targets (2009/28/EC), and its bioeconomy strategy (EC, 2012). Meanwhile, though, Sweden has also adopted ambitious forest biodiversity targets, which promotes forest conservation (SEPA, 2012) (see further Section 2). Since a few years back, a debate regarding the use of the Swedish forests has emerged, and here strong differences of opinion have been expressed. The two sides can be summarized into two main positions: "More forest conservation" and "More bioenergy based energy" (see Section 2). This study moves beyond specific arguments or postures presented in the debate, and instead, investigates the market effects from such policies, implemented individually and/or in combination.

The remainder of the paper is organized as follows. Section 2 provides a background to Swedish forest policy, as well as to the development of bioenergy use in the HP sectors, and its drivers. Section 3 presents the modeling approach, the calibration procedure with updated data, and the scenarios to be investigated. The modeling results are presented in Section 4, followed by a discussion in Section 5. Finally, conclusions and some avenues for future studies are presented in Section 6.

[1] It should however be emphasized that this study does not account for other eco-system services, such as carbon storage in forest biomass.

2. Background

Since the mid-1990s, Sweden has practiced the so-called "Swedish forestry model"; a management strategy that refers to the forest regime that evolved following the 1993-revision of the Swedish Forestry Act. Over the years, targets have been added to this model and it has, according to Lindahl et al. (2017), come to represent a "more-of-everything" strategy. Lindahl et al. (2017) identify several goal conflicts between forest production policies and environmental objectives. Instead of reducing one policy's impact to provide space for another policy area to expand, the solutions presented and introduced by the Swedish government have tended tobe characterized by the notion of expansion. In other words, the country's forestry model appears influenced by ideas of ecological modernization, and an optimistic perspective that all existing resources can be increased (Lindahl et al., 2017).

However, Swedish stakeholders' opinons differ, and the national forest debate has been quite polarized (Sandström et al., 2016; Söderberg and Eckerberg, 2013). For instance, during the spring of 2017, a lively public debate regarding the use of the Swedish forests took off, and it is still today in full bloom (DI, 2018; SvD, 2018). The participants in this debate are forest owners/lobby groups, researchers, environmental protection groups and politicians, and the arguments range from emotional opinions to standpoints based on peer-reviewed scientific research. At one side, there are the advocates for forest conservation. These (e.g. Greenpeace, left-wing party members, academic researchers) oppose clear-cutting harvesting methods and monoculture forest plantations in order to preserve biodiversity. At the other side, (mainly forest industries and academic researchers) there are the advocates for evaluations of the overall environmental benefit, i.e., arguing that the forest should be used for the purpose that generates the most significant environmental benefits (including GHG emissions mitigation). Here bioenergy is emphasized as a key solution to replace fossil fuels. As mentioned in the introduction, the two sides can be squeezed into two main positions: "More forest conservation" and "More bioenergy based energy".

In May, 2018, the Swedish Government presented a new *National forestry program* in an attempt to combine traditional forestry with biodiversity conservation (Gov. N2018.15). The program's strategy emphasizes the forest industries' economic values: "Forests – our 'green gold' – create jobs and sustainable growth in the entire country, and contribute to the development of a growing bioeconomy.” (page 2, author’s translation) (Gov. N2018.35, 2018). No new strategies for biodiversity conservation were presented, but some future options will be further investigated.

2.1. Protected and harvested forests in Sweden

Out of Sweden’s 28.3 million hectare forest, 23.6 million hectares constitute productive forest land. Approximately 11% of Sweden’s land area is protected land, out of which 9.3% are natural reserves, 1.5% national parks, and the rest consists of protected biotope areas. The shares of protection categories are shown in Figure 1. National parks are protected from logging whereas approximately 13% of Sweden’s natural reserves can legally be harvested (SCB, 2018a; Sweden Statistics and SEPA, 2016). Figure 2 shows the shares of protected forest land in each Swedish municipality. The highest percentage protected forest is located in montane ecosystems (large dark green area), which are particularly sensitive biological ecosystems vulnerable to external shocks such as roundwood harvest. Municipalities with a low percentage protected forest are typically located in the mid-north regions (light green areas).

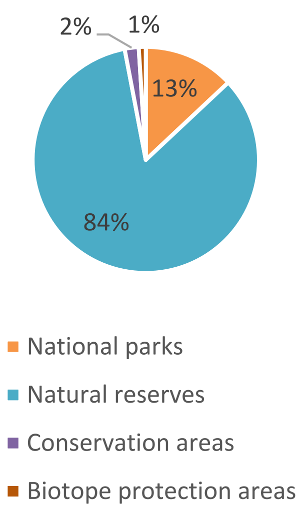

Figure 1: Percentage of four forest land protection categories in 2016. Source: SFA (2016).

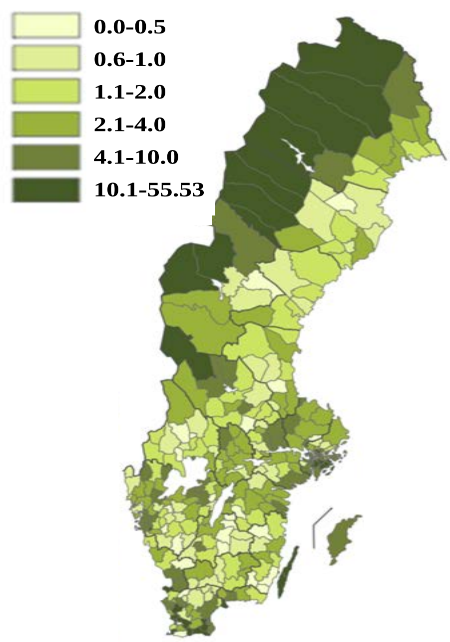

Figure 2: Percentage protected forest of total forest area in the Swedish municipalities in 2016. Source: SFA (2016).

Since 1998, the protected land area in the country has increased by 50% (out of which 66% are natural reserves, and 12% other protection categories) (SCB, 2018a). In addition to state protected forests, forest owners are also expected to voluntary set aside forest land. The total voluntarily conserved forest in Sweden in 2016 has been estimated to around 1174 thousand hectares, which equals 5.2% of all productive forest area in Sweden (SFA, 2017). For a discussion of the driving forces, the debate and implementation of forest policies concerning biodiversity in Sweden, see Simonsson et al. (2015).

Since the 1960s, both the total volume of forest harvested and the standing forest volume have increased in Sweden (Figure 3). This simultaneous increase can be explained by increased productivity in the sector, e.g. more efficient logging operations, transport and manufacturing, and increased forest growth (KSLA, 2015). Figure 4 shows the trend of a decreasing natural reforestation and increasing trend of plantations, from 1999 to the present day. Still, hectares of old forest are increasing. Between 1985 and 2012, old forest increased from 1295 to 1792 hectares, i.e., a 38% increase in 27 years. This can be explained by the increase in protected forest land (SLU, 2018). To conclude, more forest land is currently protected, but the forest land available for logging is also used more intensively.

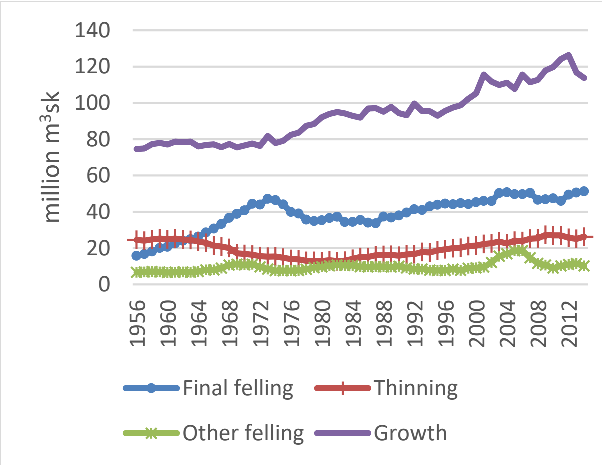

Figure 3: Forest harvest in Sweden, in million m^3sk by harvest method. Source: (SLU, 2018).

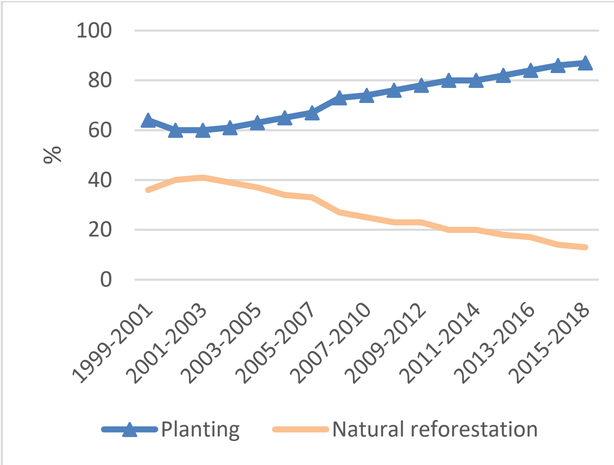

Figure 4: Planting (artificial reforestation) and natural reforestation as a share of total reforestation. Three-year averages. Source: (SFA, 2018b).

To protect biodiversity, Sweden has adopted the *Environmental quality objectives for 2020*, which include several objectives: “A rich diversity of plant and animal life”, “Thriving wetlands”, "Natural acidification only", "Reduced climate impact" and, for this case, the most crucial "Sustainable forests" (SEPA, 2012). As for the latest evaluation of these objectives, these targets were not met. The Swedish Environmental Protection Agency (SEPA) concludes that "many species and habitat types risk disappearing and ecosystems being depleted in forests and on agricultural land as well as in mountains, lakes, wetlands and the sea." (SEPA, 2018). To avoid such development, it is argued, more forest land has to be conserved. However, the amount of forest that has to be conserved is debated. Nevertheless, the Swedish government has stated the following: until the year 2020, state-protected forest land has to increase by 150 thousand hectares in particularly sensitive biological areas, and the voluntary set-aside forest land areas have to increase to about 1450 thousand hectares (Pop. 2013/14:141). The proposed voluntary set-aside is an increase by 200 thousand hectares compared to the year 2012.

To reflect the policies as well as voices in the current debate, this study will investigate the forest raw material market effects of two conservation scenarios: a low conservation scenario in which roundwood harvest is reduced by 5%, and one high conservation scenario in which such harvest is reduced by 20% (both compared to the 2016 level).

2.2. Demand for forest biomass in the Swedish energy sector

Since the 1970s, the use of biomass in the Swedish energy sector has increased significantly and forest biomass has become the main feedstock in the Swedish district heating sector (Figure 5). Biomass has also been increasingly used for power generation purposes. In 2016, total domestic bioenergy supply was estimated at 139 TWh, and it constituted 24% out of total energy supply in Sweden (Figure 6), whereof at least 80% originated from forest materials (SEA, 2017, 2018c).

The development of biomass use in the energy sector has been supported by several policy measures aiming at reducing the reliance on fossil fuels. During the mid-1970s and the 1980s, the government subsidized heat demonstration plants that could burn solid fuels (Ericsson and Werner, 2016), and the use of solid fuels was further promoted through the so-called Solid Fuel Act (SFS 1981:599). The primary reason for bioenergy's growth is the Swedish energy tax, modified in 1991 to include the carbon dioxide tax. Neither of these taxes have been levied on sustainable biofuels (McCormick and Kaberger, 2005; SFS 1990:582; Swedish Government, 2018). The energy tax was enhanced with investment grant schemes (during the periods 1991-

1996 and 1997-2002) for biomass-based combined heat and power (CHP) plants (Ericsson and Werner, 2016). Furthermore, the introduction of the renewable electricity certificate scheme in 2003 has provided further economic incentives for the use of forest-based biomass in CHP plants. In 2017, Sweden adopted ambitious climate targets; by 2045, the country should be carbon natural (Prop. 2008/09:162). Forest biomass is expected to play a key role in reaching this target (SEA, 2018b; Swedish Government, 2016).

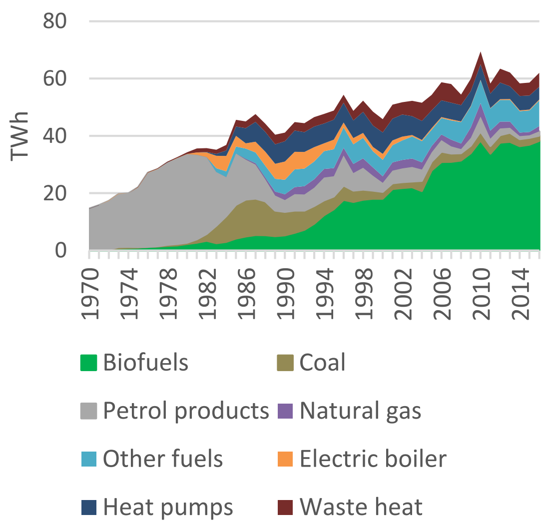

Figure 5: Input to the district heating sector 1970-2016. Source: (SEA, 2018a).

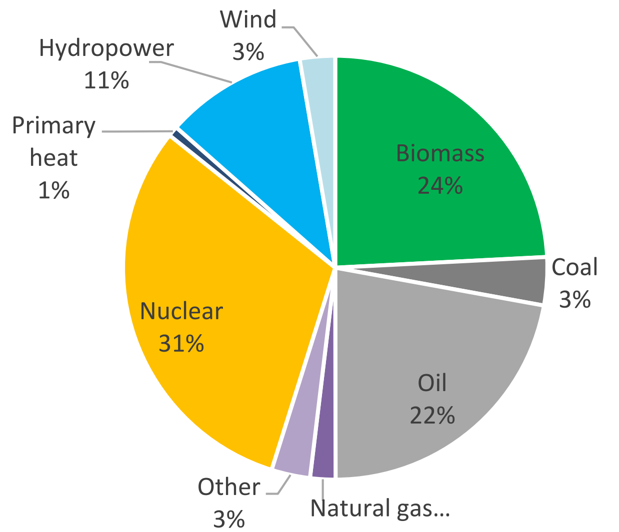

Figure 6: Total energy supply in Sweden 2016. Source: (SEA, 2018a).

The future demand for energy in the HP sector is uncertain. On the one hand, heat demand is expected to decrease in the future due to more energy efficient buildings (Ericsson and Werner, 2016). On the other hand, CHP production can be an efficient solution during periods with low intermittent production and high electricity demand levels. Gustafsson et al. (2018) investigate solutions including electricity demand reductions and converting electricity-based heating in buildings to district heating based on combined heat and power. They argue that choosing the "right" heating system is more important than reducing demand, and that it is possible to cover future electricity peak demand in Sweden by using CHP produced from forest biomass residues.

In an extensive review of future Swedish demand for forest biomass considering the techno-economic potential in the country, Börjesson et al. (2017) conclude that this demand is expected to increase by 30 TWh until 2030 and by 35–40 TWh until 2050 (compared to 130 TWh in the year 2013). They find large differences in potentials and future demand depending on the assumptions made regarding future energy efficiency improvements as well as to which extent the electrification of the transport fleet has developed (Börjesson et al., 2017).

Clearly, it is possible that bioenergy use will grow also in other sectors, most likely the transport sector (see e.g. Bhutto et al., 2016; and Mustapha et al., 2017a for a market impact analysis). In addition to HP bioenergy and transport fuels, forest biomass may also be in demand for the production of products such as green chemicals and plastics, in so-called advanced biorefinery concepts (Ulonska et al., 2018) – technologies which would also add to the competition for forest biomass. Due to several possible future outcomes for forest bioenergy use in Sweden, the present study investigates feedstock price formation and resource allocation under two scenarios of increased forest biomass use in the Swedish HP sector: 15 TWh and 30 TWh in addition to the production of 92 TWh produced from forest biomass in 2016.

3. Methods and data

3.1. Market price formation and modeling points of departure

The HP sector and the forest industries are interconnected through the market for forest biomass. Some of the forest industries' (e.g. sawmills), supply by-products (i.e. sawdust, bark, etc.), which the HP sector can use as inputs. Other forest industries', such as plywood production, compete with the HP sector for forest industry by-products. Moreover, the forest industries demand roundwood, something which causes a supply of harvesting residues, and these resources can also be used as inputs in the HP sector. This in turn reduces the competition for by-products. The price formation in the case of roundwood is dependent of the supply of roundwood (available quantities, harvesting costs, etc.), and the procurement competition for this feedstock. A by-product does not have a production cost (apart from costs for handling and transportation), but can be traded for the price determined by the demand in the market. Since by-product supply is constrained by the production of the main product, the marginal cost curve is expected to be flat for low levels of demand and increase sharply (exponentially) when supply is approaching the constraint set by the production level for the main product (Söderholm and Lundmark, 2009).

Increased HP production from forest biomass is expected to increase the overall feedstock prices in the forest raw material market (see e.g. Carlsson, 2011; Schwarzbauer and Stern, 2010 for empirical evidence). However, Lauri et al. (2017) investigate bioenergy demand targets and find only moderate forest raw material feedstock price rises. They argue that increased returns on by-products can spur sawmills to produce more sawnwood, something that in turn generates an increased by-product supply and helps to reduce the overall feedstock price increase. In the present study, this by-product effect is expected to be non-existent or very small since sawnwood production cannot increase due to input restrictions on sawlogs; domestic sawlog harvest, as well as roundwood imports (see further Section 3.4), are restricted to 2016's levels (pulpwood cannot be used in sawnwood production). All the three studies above find sawmills to benefit from increased by-product prices, and that the panel and paper industries would be worse off due to increased input prices; a result expected also in this study. However, the magnitude of these effects are not known. A decrease in the supply of roundwood implies a reduction in sawnwood production, and a proportionally decrease in the supply of by-products, as well as decreased supply of harvesting residues in proportion to the decrease in roundwood harvest. Thus, reduced harvest will intensify the competition for forest raw materials. This can potentially lead to feedstock substitution in the HP sector where forest raw materials could be substituted with fossil fuels, as well as lead to structural transformations. Kallio et al. (2018) find that reduced harvest levels in the EU and Norway would lead to increased raw material prices in the global market. In this study, reduced harvest in Sweden is expected to increase feedstock prices in Sweden (but not in the world market). These increases are in turn anticipated to affect the allocation of forest biomass across the various sectors using this resource. Forest conservation in Norway and Finland are shown to have low price impacts on roundwood prices in the case in which imports can substitute for domestic materials. In the case imports are restricted (increased forest conservation among trade partners), roundwood prices are affected more substantially. Sawmills are found to be worse off under forest conversation whereas the paper production is unaffected (Bolkesjo et al., 2005; Hanninen and Kallio, 2007). In the present study, import possibilities are restricted and thus, price increases on roundwood can be expected.

3.2. The SFSTMII model

This research is carried out using the so-called Swedish Forest Sector Trade Model (SFSTM) II, developed by Lestander (2011) and further refined by Carlsson (2011). The modeling structure and general assumptions about supply and demand curves in the SFSTM are similar to those adopted in the Global Trade Model (GTM) family, developed at IIASA in the 1980s by Kallio et al. (1987), later EFI-GTM (Kallio et al., 2004). SFSTMII is a static, one-period national spatially explicit forest sector model, (i.e., a partial equilibrium model). In the model, Sweden is divided into four regions (see Figure 7).

Region 1 = 'North': Norrbotten, Västerbotten, Jämtland, Västernorrland
Region 2 = 'East': Dalarna, Gävleborg, Västmanland, Uppsala, Stockholm

Region 3 = 'West': Värmland, Örebro, Västra Götaland
Region 4 = 'South': Södermanland, Östergötland, Jönköping, Kronoberg, Kalmar, Gotland, Halland, Blekinge, Skåne

Figure 7: The four Swedish regions in SFSTM II. The regions consist of counties (listed to the right in the figure). Source: SDC (2017).

The theoretical framework underlying the modeling simulations relies on Samuelsson (1952) theory of perfectly competitive spatial price equilibriums[2]. The four regions trade raw materials and forest industry products with each other as well as with a region representing the Rest of the World (ROW).[3] ROW is incorporated as a trade partner to the domestic regions in order to reflect the international competition for forest biomass and forest industry products. Transport costs of biomass are included to reflect the differences in distances between the regions. Imports occur when a product is cheaper in another region (taking into account transportation costs). Thus, raw

[2] Actors in the forest raw material market may possess some degree of market power, often pulp mills due to large sunk costs (Murray, 1995). However, with increasing international trade, market power is expected to decrease, i.e., the law of one price (LOP) will kick in. Indications of such developments are found in the global pulpwood market (Olmos and Siry, 2015), and in the roundwood markets (Olmos and Siry, 2018; Toivonen et al., 2002).

[3] The definition of ROW in this paper includes the EU Member States and Norway.

materials (e.g. sawlogs) and products (e.g. sawnwood) are assumed to be perfect substitutes across the various regions (i.e., homogenous goods).

SFTSM II includes the forest owners' raw material supply of roundwood and harvesting residues, the forest industries' demand for feedstock, the forest industries' and HP production technologies, as well as the supply of final products, intermediate products and by-products. In this way, the model enables analyses of feedstock competition between the forest industries and the bioenergy use in the HP sector. Figure 8 provides a schematic illustration of the SFSTMII. The box at the top illustrates the supply of raw materials, the large box in the middle, the interconnections between the forest industries and the HP sector. Finally, the bottom box illustrates the demand for forest-based end-use products and HP energy.

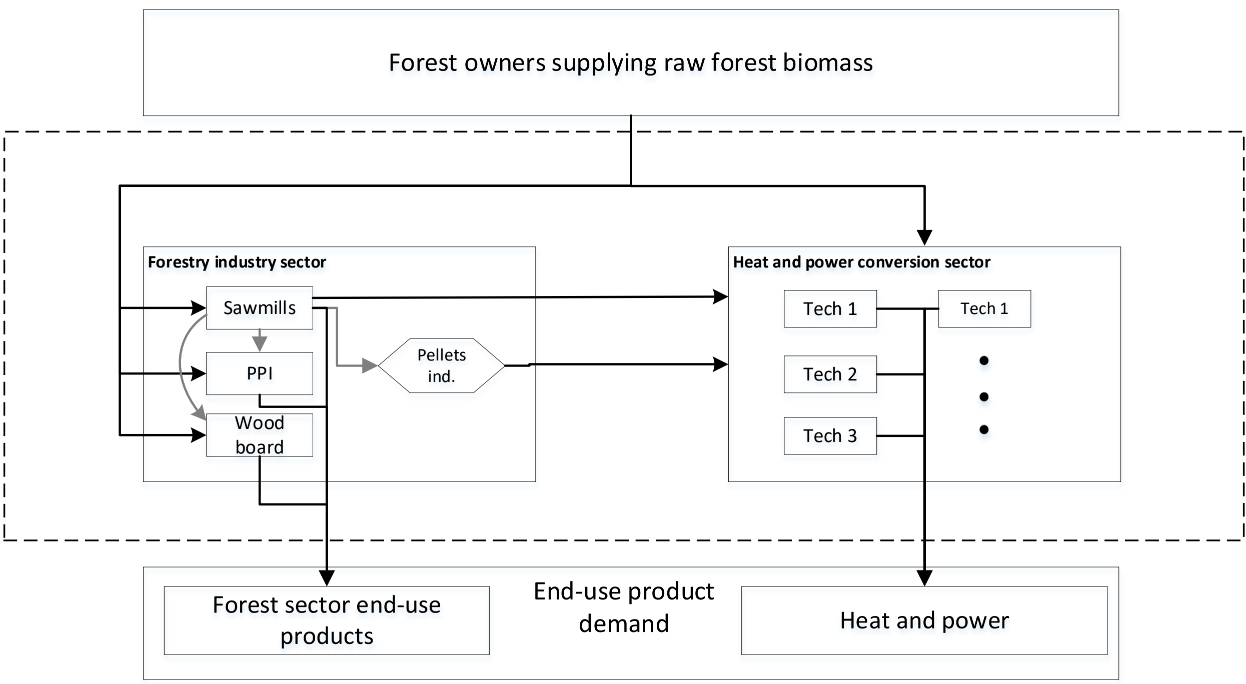

Figure 8: Schematic illustration of the SFSTMII model.

Production is modeled based on input-output coefficient analysis. If a plant is producing at its maximum capacity and demand increases, new capacity is added to model subject to an investment cost.[4] In order to produce HP using forest biomass, the model can choose the following feedstocks: wood chips, sawdust, bark, pellets (processed from wood chips, sawdust or bark), and harvesting residues. Unlike Carlsson (2011), this study does not allow pulpwood to be used in the HP sector. This assumption is in line with the European Union's waste hierarchy, established in the EU Directive 2008/98/EC and re-established in the proposed REDII directive (EU 10308/18, 2018).

3.3. Model calibration

The latest version of the SFTSM II includes data from 2008. In this paper, the data have been updated and calibrated to the year 2016. A summary of the updated data is provided below, and it is presented in detail in Appendix. SFTSM II contains four categories of data for both the Swedish regions and the ROW:

a) Harvest levels (regional, three tree species, two roundwood types, harvesting residues);
b) Regional production (sawnwood, paper, HP bioenergy etc.) for a total of 30 end-use products and intermediate products (for all regions;
c) Demand (use) for the products in b) and for forest raw materials (feedstock in production); a total of 140 different activities. One product demand can be satisfied with different activities in b), e.g. HP bioenergy can be produced from sawdust as well as bark, etc.
d) Prices of forest raw materials, products, and HP energy.

Data have been gathered mainly from the Swedish Forest Agency (SFA), the Swedish Forest Industries Federation (SFIF), Statistics Sweden (SCB), and FAOSTAT. Much of the available data concerning forest industry production has changed since 2008, and this is mainly due to the closedown of the Statistical Yearbook of Forestry produced by Statistics Sweden. For this reason, harvest data and data on production of sawnwood, pellets etc. have instead been obtained from several sources and processed to fit into the regional disaggregation presented in Figure 7.

[4] The latter is annualized with a factor of $\sigma = 0.08$, which is equivalent to a 5% interest rate and a production plant lifetime of 20 years. For a more in-depth explanation of the model's equations, elasticities assumed, etc., see Carlsson (2011).

Moreover, the fossil fuel price for the energy sector is assumed to be equivalent to the price for heavy oil, which in 2016 equaled 70 EUR/MWh (SPBI, 2018).

3.4. Scenarios

3.4.1. The Baseline scenario

The Baseline scenario comprises simulated production, trade etc. for the year 2016, calibrated with 2016 data. The baseline scenario thus reflects the Swedish forest raw materials market when neither additional demand for bioenergy in the HP sector, nor any harvest restrictions have been implemented in the model.

Although the model does not describe the global markets for forest raw materials in any detail, it is necessary to briefly address how imports are addressed in the analysis. World demand for pellets and other forest fuels are increasing. Between 2012 and 2016, EU imports of wood pellets from non-EU countries increased by almost 80% (reaching almost 8000 million tons) (Eurostat, 2018). With current policies, this development is expected to continue (Balan et al., 2013), and increased world competition is expected to drive up forest biomass feedstock prices (Johnston and van Kooten, 2016; Jonsson and Rinaldi, 2017). Thus, it is unrealistic to assume that all countries could satisfy an increased domestic demand for biomass feedstock with increased imports from other countries. For this reason, the import levels in all scenarios, including the baseline, are constrained to 2016 levels. In 2016, the observed net-import level of pellets in Sweden was 40 thousand tons, and imports of wood chips, particles and residues amounted to 1800 thousand m^3 (FAO Statistics, 2018). Because neither pellets nor by-product imports are strictly monitored, the level of pellets imports is allowed to increase up to 50 thousand tons and the corresponding levels for wood chips, particles and residues up to 2000 thousand m^3 in the model runs.

3.4.2. Bioenergy demand targets and harvest restrictions

In addition to the baseline scenario in which 92 TWh bioenergy HP is produced, eight scenarios are investigated. These are presented in Table 1. Scenarios 1.1-1.2 involve two HP bioenergy demand targets: 15 TWh and 30 TWh, i.e., a total of 107 and 122 TWh (and assuming harvest levels to be constant at the 2016 levels). Scenarios 2.1 and 3.1 address a 5% and a 20% reduction in roundwood harvest levels compared to 2016 levels (assuming 2016 HP bioenergy levels), while scenarios 2.2-3 and 3.2-3 address the presence of combined bioenergy demand targets (the additional 15 and 30 TWh) and reduced harvest levels (by 5 and 20%, respectively). In the model, regional demand for HP is estimated based on population density. However, since the exact location of future HP bioenergy demand is unknown, the HP bioenergy demand targets are implemented on a national scale, i.e., the conversion of forest raw materials in the HP sector may take place in any of the four domestic regions. Moreover, the share of reduced harvest (increased forest conservation) are equal across regions and tree species, i.e. implying higher absolute decreases in the forest-rich regions.

	Bioenergy demand targets in the HP sector: production in addition to 2016 bioenergy levels			Percentage reduction from observed harvest levels in 2016		
Scenario	0 TWh	15 TWh	30 TWh	0 %	5 %	20 %
Baseline	x			x		
1.1		x		x		
1.2			x	x		
2.1	x				x	
2.2		x			x	
2.3			x		x	
3.1	x					x
3.2		x				x
3.3			x			x

Table 1: overview of scenarios

4. Simulation results

4.1. Bioenergy demand targets

Increased demand for bioenergy in the HP sector implies an increased use of eligible feedstock for such an increase, i.e., forest industry by-products (raw or processed to pellets) and harvesting residues. As shown in Figure 8 and Figure 9, the prices of industry by-products, pellets and harvesting residues increase with increased HP bioenergy production, and more intensely so for the higher target (30 TWh). The relative price of sawdust increases the most, something which can be explained by a strong increase in the demand for sawdust (see further below).

As shown in Figure 9, the production of pellets triples in the presence of 30 TWh additional HP bioenergy, and there is a significant increase in price. The price increase of pellets is however less sharp than that for the by-products, this due to a relative high baseline price (world market price for pellets) and the diversification of feedstocks in pellets production.

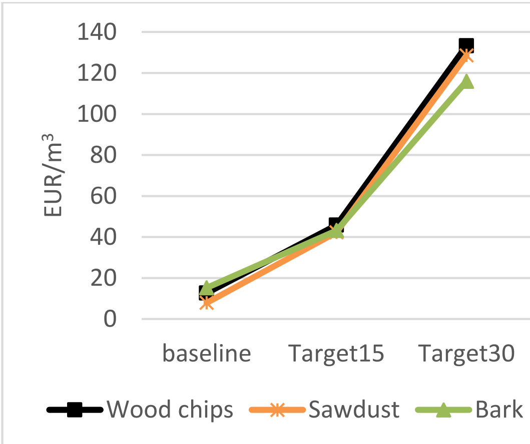

Figure 8: Prices for industry by-products in the baseline scenario and the two HP bioenergy demand scenarios (EUR/m^3) (with 2016 harvest levels).

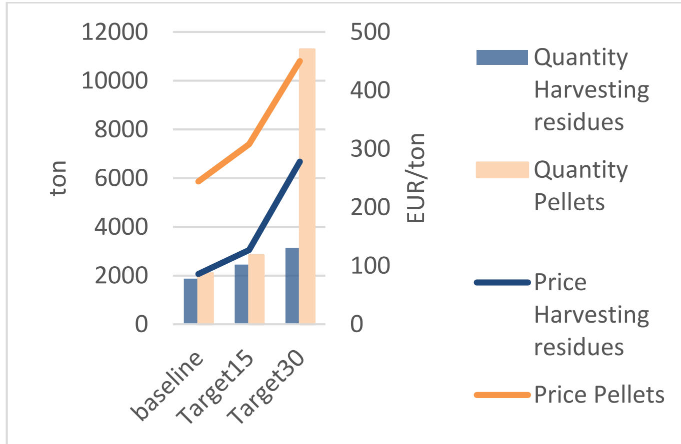

Figure 9: Production of pellets (processed by-products) in ton, the price development of pellets (EUR/ton), harvested residues in Oven Dried Ton (ODT) and the price development of harvesting residues (EUR/ODT), in the baseline scenario and the two HP bioenergy demand scenarios.

Figure 10 shows the pellets production by feedstock. Sawdust (and a small amount of wood chips) is used to produce pellets in the baseline scenario. However, when pellets production increases and the sawdust price increases, the pellets industry shifts away from mainly using sawdust to wood chips and bark. Only very small amounts of bark are used in the baseline scenario, but this feedstock becomes competitive following the increase in the prices of sawdust and wood chips.

A similar feedstock shift can be observed in the HP sector (see Figure 11). The total amount of energy production in the HP sector is constant across the various scenarios (i.e., based on the assumption of a fully own-price inelastic demand) and equals 100 TWh.[5] Introducing demand targets for HP bioenergy therefore implies a decreased use of fossil fuels (grey bars to the left in Figure 11), and an increased use of forest biomass. Our simulations show that the HP bioenergy targets are mainly satisfied with an increased use of pellets but also harvesting residues. The declines in wood chips, sawdust and bark use that can be observed in Figure 11 does not represent actual declines in the use of forest raw materials; they rather indicate a re-allocation of forest raw materials from, for instance, sawdust to processed sawdust in the form of pellets. This can be explained by the efficiency gains from reduced transport costs; raw materials are bulky and has a

[5] The forest industries' internal use of black liquor to produce electricity and heat is excluded from the analysis.

lower calorific value compared to pellets. For increased HP bioenergy (which cannot be traded across region), transport distances are increasing and pellets increase in demand.

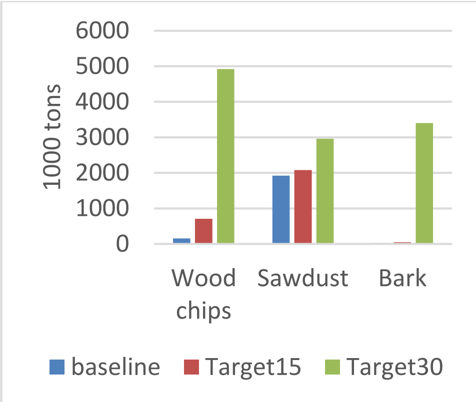

Figure 10: Pellets production by feedstock (thousand tons).

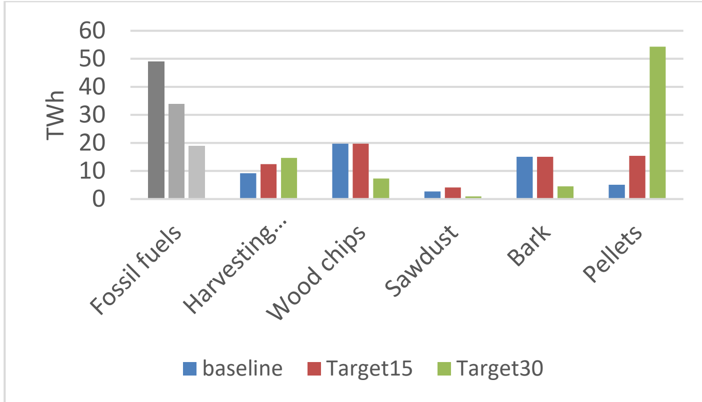

Figure 11: Feedstock composition in the HP sector (TWh).

In terms of forest industry production, paper production declines by 8% in the presence of the 30 TWh target, and all board (i.e., fiberboard, particleboard and plywood board) production shuts down already with the implementation of the 15 TWh target. With decreased production in the board industry, demand for pulpwood decreases, and therefore also the price of pulpwood.

Although harvest is restricted to 2016 levels, an insignificant increase in sawnwood production can be observed. This is made possible due to a small under-utilization of roundwood imports in the baseline scenario. However, if harvests were not restricted to 2016 levels, but could increase with increasing demand, sawnwood production is likely to have increased in response to increased profitability from supplying forest industry by-products. The sawnwood industries compete for the available sawlogs, and the price of sawlogs increase from 37 to 98 EUR/m^3.

In conclusion, increasing HP bioenergy causes an increased use of all forest biomass feedstocks available to the HP sector. The use of pellets (processed sawdust, wood chips and bark) increases the most, but there is also a more modest increase in the use of harvesting residues. The competition for sawlogs increases, but decreases for pulpwood. All board industries shut down in the presence of a 15 TWh increase in HP bioenergy. In other words, the increased competition for sawdust from the HP sector raises the price of this feedstock, in turn making board production unprofitable in Sweden.

4.2. Increased forest conservation

Increased forest conservation implies reduced harvest of roundwood, i.e., sawlogs, pulpwood and harvesting residues. This sub-section compares feedstock prices and feedstock composition for three scenarios: the baseline scenario, reduced harvest by 5% and reduced harvest by 20%. The demand for forest biomass in the HP sector is assumed to be constant at the 2016 levels. First thing to note is that all by-product prices and forest residues decrease for a harvest reduction of 5% (see Figure 12 and Figure 13). The price of wood chips and bark remains at the new low level also in the presence of a 20% decrease, the price of harvesting residues continues to fall, whereas the price of sawdust increases (but it is still lower than in the baseline scenario).

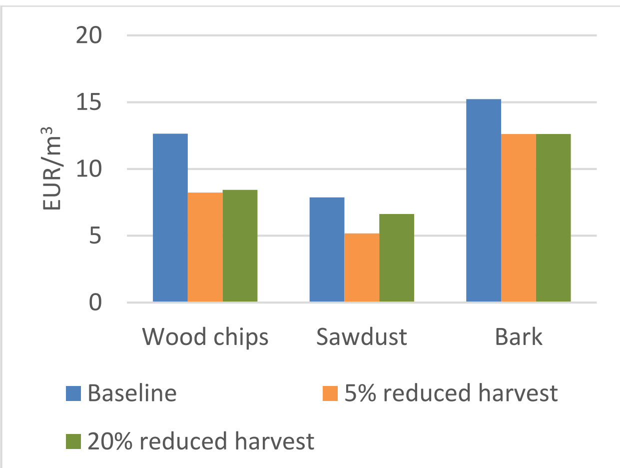

Figure 12: By-product prices under forest conservation scenarios (EUR/m3).

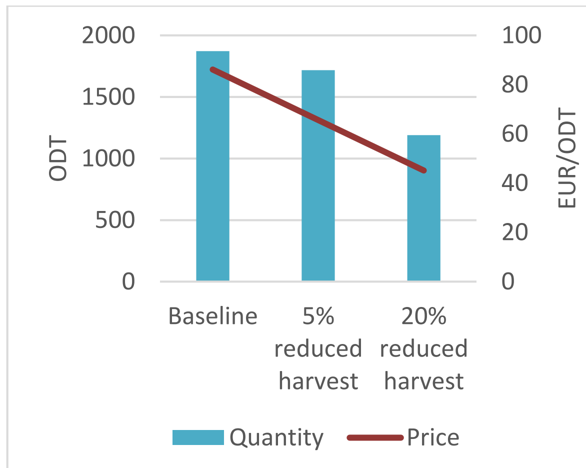

Figure 13: Output of harvesting residues (left axis, ODT), and the price of harvesting residues (right axis, EUR/ODT).

At first glance, the price falls for forest industry by-products and harvesting residues, respectively, appear unexpected since the competition for forest raw materials should become more intense with more forest conservation. With reduced roundwood harvest, all forest industries decrease their production; sawnwood production decreases by 6%, the production of paper products by 4% and, not least, particleboard production by 43%. Sawnwood production has to decrease with reduced sawlog harvest levels. Paper production has to decrease with reduced pulpwood harvest; paper is produced from mechanical and chemical pulp, which is produced mainly from pulpwood (and recovered paper). However, the other feedstocks in pulp production are by-products (e.g. wood chips). With reduced pulp production, the demand for by-products decreases, and this makes the prices of these drop. The same logic goes for the board production; the board industry uses by-products as input, but also pulpwood. With increasing pulpwood prices, the board industry reduces (and even halts) its production, and as a result sawdust is less in demand.

Thus, decreasing production of pulp (intermediate product in paper production) and board products causes a price fall for by-products. The price of sawdust decreases for a 5% harvest reduction. The board production continues to fall with increased forest conservation but to due to increased competition for available feedstock when also sawnwood production decreases, the price drop is less significant in the 20% harvest reduction scenario (see Figure 12).

As shown in Figure 13, the harvest of forest residues decreases (proportionally to the decline in roundwood harvest) and the price of harvesting residues decreases. The price drop for harvesting residues is a response to the price drop for by-products; the HP sector prefers the industrial by-products over harvesting residues due to calorific values and conversion costs. For this reason, the lower prices of by-products make harvesting residues redundant, something which in turn causes the price of harvesting residues to drop. For a 20% harvest reduction, the HP sector uses a little less harvesting residues (1.35 TWh), a decrease which is then replaced by sawdust (0.95 TWh) and wood chips (0.40 TWh).

4.3. Bioenergy demand targets combined with forest conservation

This sub-section investigates the forest raw material market effects from introducing bioenergy demand targets *in combination with* increased forest conservation. The simulated forest industry by-product prices are shown in Figure 14-Figure 16. The colors refer to the additional bioenergy demand, and the x-axes represent the forest conservation in terms of reduced harvest levels. As observed above, an increase in the demand for forest biomass in the HP sector causes sharp price increases for forest industry by-products, while solely reducing harvest levels instead generates moderate price decreases due to declines in forest industry production. In the mixed scenarios in which HP bioenergy targets are introduced under harvest restrictions, the increases in by-product prices are more moderate compared to the scenario without any harvest restrictions. As shown in Figure 14, the price of sawdust increases sharply for increased forest biomass in the HP sector under no harvest restriction (almost to 130 EUR/m^3), but this increase is less sharp in the 5% and 20% harvest reduction cases (below 20 EUR/m^3). Since by-products are substitutes in the HP sector (and to some extent in the forest industries), the prices of by-products have similar price developments. The by-product price increases are dampened by the reduced competition for these feedstocks as the forest industries decrease their production due to reduced available roundwood and increases in the roundwood prices.

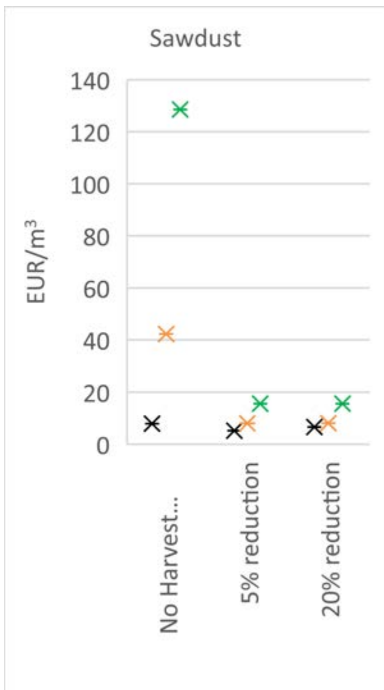

Figure 14: The price of sawdust (EUR/m^3) in scenarios of increased HP bioenergy and reduced harvest.

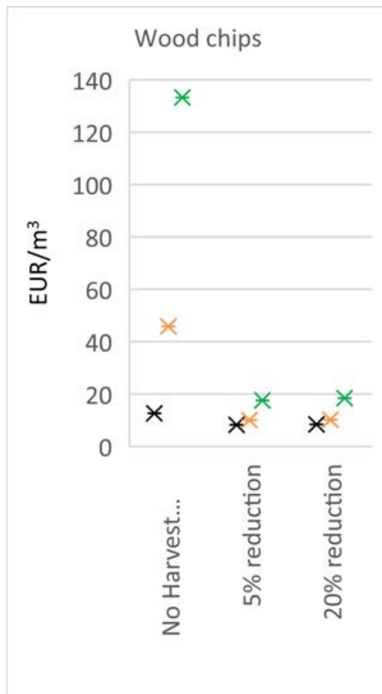

Figure 15: The price of wood chips (EUR/m^3) in scenarios of increased HP bioenergy and reduced harvest.

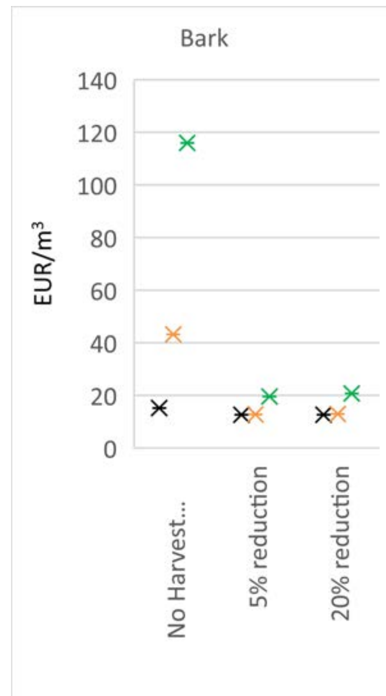

Figure 16: The price of bark (EUR/m^3) in scenarios of increased HP bioenergy and reduced harvest.

Simulated forest industry production levels are shown in Figure 17-Figure 19. Whereas sawnwood production is pushed up in the increased HP bioenergy scenario for no harvest reduction[6], sawnwood production decreases significantly when introducing HP bioenergy targets under reduced roundwood harvest, simply due to lack of inputs (decreased sawlog harvest). Paper production is in general decreasing under increased HP bioenergy production due to a tightened competition for by-products. Introducing the 5% harvest restriction does not affect this pattern. However, in the 20% harvest reduction scenario, more paper production is observed for all levels

[6] As noted above, this is possible due to a small under-utilization of roundwood imports in the baseline scenario.

of HP bioenergy compared to the no harvest restriction and the 5% harvest reduction scenarios. These increases are at the expense of the board industry, which shrinks to low levels already for no additional HP bioenergy in the 20% harvest reduction scenario (shown in Figure 19).

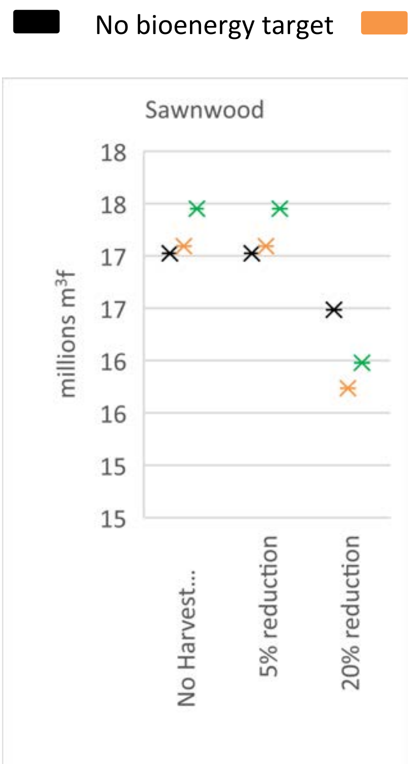

Figure 17: Sawnwood production (thousand m^3) in scenarios of increased HP bioenergy and reduced harvest.

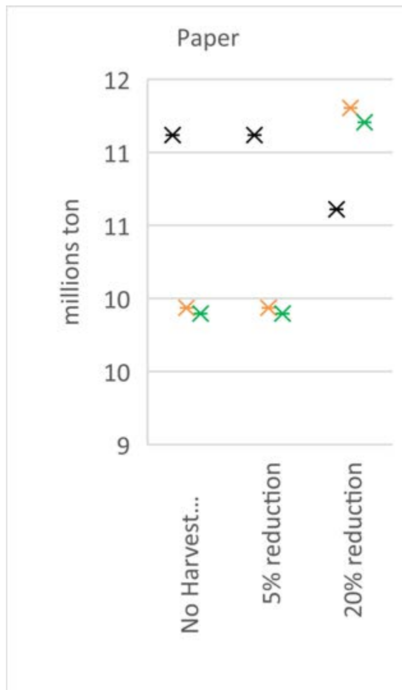

Figure 18: Paper production (thousand tons) in scenarios of increased HP bioenergy and reduced harvest.

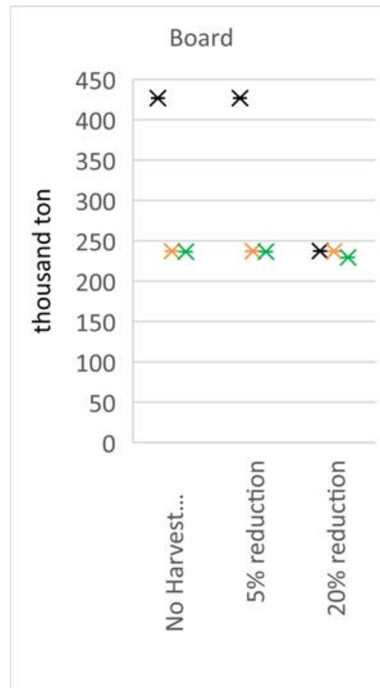

Figure 19: Board production, particle board, fiberboard and plywood aggregated, (thousand tons) in scenarios of increased HP bioenergy and reduced harvest.

In addition to the imposed harvest restrictions, increasing HP bioenergy demand under increased forest conservation is shown to cause additional reductions in harvest levels (Figure 20-21). When introducing the HP bioenergy demand targets, the required 5% harvest reduction leads to a 10% harvest reduction, and the 20% reduction leads to a 31% decrease. The additional reduction in roundwood harvest can be explained by increased roundwood prices caused by the harvest reductions.

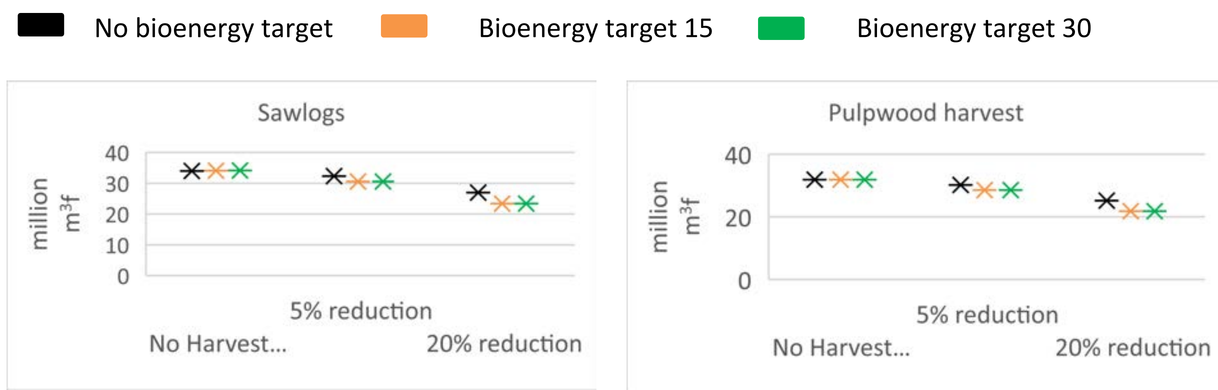

Figure 20: Sawlog harvest (million m^3f) in scenarios of increased HP bioenergy and reduced harvest.

Figure 21: Pulpwood harvest (million m^3f) in scenarios of increased HP bioenergy and reduced harvest.

The feedstock composition for increased bioenergy in the HP sector seems to differ substantially between the baseline scenario (Figure 22), and the scenarios with harvest restrictions (Figure 23-24).

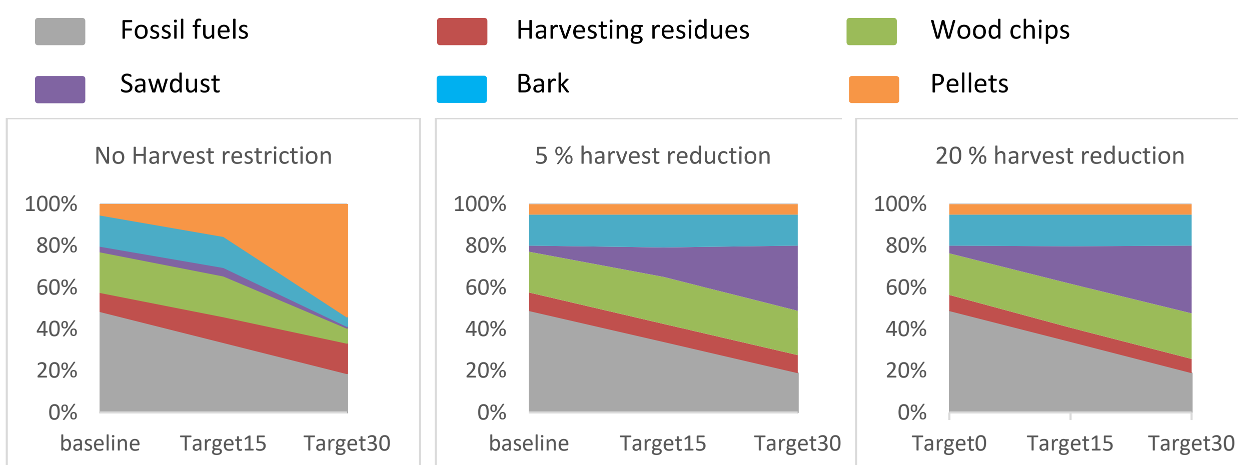

Figure 22: Feedstock composition in the HP sector under 2016 harvest levels

Figure 23: Feedstock composition in the HP sector under the minus 5% harvest scenario.

Figure 24: Feedstock composition in the HP sector under the minus 20% harvest scenario

The use of pellets increases significantly with increasing HP bioenergy targets in the case where there are no harvest restrictions (Figure 22), but it is constant in the scenarios with reduced harvest. In contrast, as more stringent forest conservation policies are implemented, the use of sawdust instead increases substantially in the HP sector (Figure 23-24). However, sawdust is also the major input in producing pellets, and for this reason the feedstock composition is practically very similar across harvest levels. The key difference lies instead in whether the sawdust feedstock is processed to pellets or not. Pellets is generally cheaper to transport than sawdust due to its higher energy content per ton, but it comes with an intermediate production cost. When feedstock demand increases under harvest restrictions, feedstocks tend to be transported for longer distances, and this makes the processing of sawdust to pellets more economical.

Increased bioenergy targets in the HP sector causes the use of harvesting residues to increase in the No Harvest reduction scenario due to a relative price decrease compared to forest industry by-products (Figure 22). This effect is not equally present in the reduced harvest scenarios due to the decreased supply of harvesting residues.

5. Discussion

An increased demand for forest raw materials following the introduction of HP bioenergy targets is expected to lead to increased competition for forest raw materials and push up feedstock prices (Söderholm and Lundmark (2009), for empirical evidence e.g. Carlsson (2011)). Furthermore, the increase in forest industry by-product prices could spur sawmills to increase production due to increased returns on by-products, and therefore an expansion of bioenergy production is likely to create winners –sawmills due to increased return on by-products, and losers – pulp and paper industries due to increased input prices (Lauri et al., 2017; Trømborg et al., 2013). In the present paper, sawmills cannot increase their production, and the synergy effects between sawmills and HP bioenergy production are absent, and thus higher by-product prices cannot be mitigated by increased by-product supply. Thus, considerable by-product price increases were expected, and the industries demanding these products were expected to be negatively affected. This study confirms this course of events in the scenarios for which only HP bioenergy is increased, but for the scenarios in which HP bioenergy increases are introduced simultaneously with reduced roundwood harvest, the results display a more complex course of events. The expected losing industries are indeed losing, yet they are losing so much that the by-product price increase is mitigated. Thus, all forest industries are worse off in the case where bioenergy targets and forest conservation policies are introduced simultaneously, but the HP sector is actually better off due to reduced competition from forest industries. The structural transformations caused by HP bioenergy policies is found both in the scenario with current harvest levels and under reduced harvest. Thus, reducing forest harvest levels does not seem to fundamentally affect the outcome of the structural transformation caused by the HP bioenergy policy intervention.

In previous studies, forest conservation in Norway and Finland has been shown to lead to reduced sawnwood production (Bolkesjo et al., 2005; Hanninen and Kallio, 2007); a finding which is confirmed also in this paper for Sweden. Similar to Bolkesjo et al. (2005) and Hanninen and Kallio (2007), the present paper observes increased pulpwood prices with increased forest conservation. However, unlike the present paper, Bolkesjo et al. (2005) and Hanninen and Kallio (2007) find that the pulpwood price increase do not effect the paper and board production; Bolkesjo et al. (2005) find that that most pulp and paper mills continue to produce on the capacity limit as a results of other factors in the production decisions than the input prices, e.g. price and income sensitivities, demand of forest products demand and current production capacities.

This outcome difference can be explained by differences in model assumptions, national factors and modeling design (domestic demand, elasticities, initial production levels, substitution possibilities etc.). For instance, unlike Finland and Norway, Sweden do not produce paper and board products at its production limits in the baseline scenario. Rather, Sweden has experiences a continuous decrease in production in some of its forest industries during the past ten years, especially the in the board industries due to increased feedstock competition with the HP sector. Furthermore, whereas the present study adopts strict import restrictions, the Finish study allows 30% of the decline in domestic harvests to be substituted with imports from other countries (Hanninen and Kallio, 2007). Moreover, the present study assumes a considerably more aggressive conservation scenarios; at most, 20% of Sweden's roundwood harvest is reduced; Bolkesjo et al. (2005) assumes at most a forest conservation of 11.9%, and Hanninen and Kallio (2007) at most a 5% forest conservation for one particular region with old-grown forest in Finland. The differences between these studies regarding the simulated outcome of the national pulp and paper sectors is shed light on the importance for studies considering countries different markets, as well as caution is to prefer when it comes to compare the outcome of studies.

Dixon et al. (2013) found that the combination of two EU policies, one promoting bioenergy and the other promoting forest conservation, would lead to increased food prices in economically vulnerable countries due to increased land prices. The present paper shows mitigated feedstock price increases in the scenario for which the policies are introduced simultaneously. The different results are due to several factors. First, Dixon et al. (2013) assess an increased use of first generation biofuels for which food prices and bioenergy are linked via the competition for land. In the present paper, the land will only grow forest, but the biomass allocation may change due to changes in demand and price formation. Some industries were shown to disappear, which causes more modest price increases. However, food consumption cannot cease (assuming limited possibilities to import food in developing countries), and thus in the Dixon et al. case, prices continue to be pushed upwards.

Furthermore, Dixon et al. (2013) assess policies assumed to be implemented at the EU level, and therefore the policies could be expected to affect world market prices. The inclusion of several countries allows for assessments of the impact of changing world market prices. The present paper assesses one country's market under nationally implemented policies. Alone, these policy interventions cannot be expected to affect world market prices. Nevertheless, in a scenario in which also other countries (e.g. the EU Member States) would implement similar bioenergy and forest conservation policies as assumed for Sweden in this paper, a different outcome would be expected. In the long run, increasing product prices could lead to structural transformation in which paper and board products are replaced by new materials, more advanced recycling or new technology – these are all possible developments that are difficult to fully capture in partial equilibrium modeling.

At a general level, the HP sector can choose between using fossil fuels and biomass. In the baseline scenario, forest biomass is cheaper than fossil fuels, and it is therefore the natural choice of feedstock. However, with increasing forest biomass prices caused by increased competition or reduced supply, the feedstock composition is not given. Geijer et al. (2011) found that the forest conservation policy aiming at reducing GHG emissions in Sweden could actually lead to increased GHG emissions, this due to a substitution away from forest biomass to fossil fuels in the HP sector. The present paper shows that reducing harvest by 20% (no targets for bioenergy) does not affect the shares of fossil fuel and biomass use in the HP sector. This can be explained by the larger price difference between fossil fuels and biomass in Sweden compared to Norway, due to Sweden's higher carbon dioxide tax. Accompanied by, for instance, Geijer et al. (2011), this paper sheds light on the forest raw material market's complexity under policy interventions.

The policy interventions assessed in this paper are built upon policies motivated by market failures (i.e., lack of a market price for biodiversity, the external cost of carbon emissions from the use of fossil fuels, etc.). The results in this paper show that the assessed policy targets lead to an increased competition for forest raw materials, and eventually even shut-downs in the board industries. Increased competition following an internalization of market failures is not in itself a result of inefficient markets, and thus something that motivates further policy interventions. Still, for an efficient policy implementation in the case of climate change and forest conservation, the policy targets have to be well adapted to the underlying market failures. The question of whether the existing policies achieve this is beyond the scope of this paper, but it constitutes an important aspect to consider in future research. Furthermore, different policy designs (achieving the same underlying targets) may affect the markets in different ways. In this paper, no specific policy design has been assessed, rather exogenous interventions (targets). Nevertheless, the analysis in paper provides a useful point of departure for such policy analyses.

6. Conclusions and avenues for future research

The present paper has assessed a possible continuation of the so-called "more of everything" forest management strategy in Sweden. Specifically, the paper has addressed the question of how two different policies – both implying an increased demand for forest ecosystem services – may affect the competition for forest raw materials.

We find that promoting bioenergy and forest conservation tends to have partly opposite effects on forest industry by-product prices. Moreover, combining the two policies reduces the forest industry by-product price increases, this compared to the case where only the bioenergy-promoting policy is implemented. For this reason, the HP sector could be less negatively affected in terms of increased feedstock prices if bioenergy demand targets are accompanied by increased forest conservation. This is due to increasing pulpwood prices, which reduce pulp, paper and board production, in turn mitigating the competition for forest industry by-products. Notably, the competition even implies a shutdown of the domestic board industry. Overall, the paper illustrates the complexity of the forest raw material market, and the importance of considering demand and supply responses within and between sectors in future energy and forest policy designs.

Future developments, including future demand for forest industry products (pulp and paper or green chemicals), demand for energy (development of smart building, transport fuels, etc.), and needs for forest conservation, are all uncertain variables. So-called second generation (2G) liquid biofuels are expected to be cornerstones in greening heavy transports and the aviation sector, for which policies to support such a development have been adopted (Bessou et al., 2011; EU 10308/18, 2018; Mustapha et al., 2017b). In a future study, the model presented in this paper could be extended with a 2G biofuel module, and the impact of 2G policies could be examined on the HP sector as well as forest industries. Such an extended model could also be soft-linked to a supply chain model in order to evaluate different biorefinery concept while considering price formation of feedstocks. Furthermore, adding more regions to the SFSTMII model would allow for detailed analysis of forest conservation in specific regions, and its effects on specific industry plants.

At a general level, this paper has highlighted the importance of considering price formation in forest biomass markets when developing forest policies. Depending on the policy design, and not the least combination of policies, competition for raw materials can lead to different outcomes including synergy effects and structural changes. Future research should therefore also devote increased attention to the issue of policy design, and how various designs could affect the forest raw materials markets given their complex interactions.

Acknowledgments

The work has been carried out under the auspices of Forskarskola Energisystem, financed by the Swedish Energy Agency. The author thanks Patrik Söderholm at Luleå University of Technology who has provided insight and expertise that greatly assisted the research.

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Appendix: modelling definitions, data and assumptions

- All data are from the year 2016.
- Plant investment costs, own-price elasticities, income elasticities and IO-coefficients are from Carlsson (2011), and are not written out in this paper.
- Trade equals consumption minus production, i.e. net-imports = consumption – production. Positive net-imports implies imports, whereas negative net-imports implies exports. Trade of pellets and by-products are presented for both imports and exports.

Abbrevations	Explanations
SpruceLog	Logs from spruce trees
PineLog	Logs from pine trees
NonConLog	Logs from non-coniferous trees
SprucePulp	Pulpwood from spruce trees
PinePulp	Pulpwood from spruce trees
NonConPulp	Pulpwood from non-coniferous trees
SpruceSawn	Sawnwood from spruce
PineSawn	Sawnwood from pine
NonConSawn	Sawnwood from non-coniferous
MechPulp	Mechanical pulp
ChemPulp	Chemical pulp
RecoveredPulp	Recovered pulp from recycling

Appendix Table 1: Abbreviations of forest raw materials and forest industry products, and their correspondent explanations that are used in this Appendix.

The rest of the Appendix is organized as follows: a) presents observed harvest levels and exogenous supply of forest raw materials. b) presents the observed production in forest industries, and c) the prices of those. The heat and power demand is derived by feedstock in the HP sector in d). e) presents the reference use levels of forest industry products. f) presents trade quantities of forest raw materials between Sweden and the ROW, levels to which trade is restricted in the scenario analysis.

a) Harvest

Roundwood type	Sweden	ROW
Sawlogs, coniferous,	35700	
Sawlogs, non-coniferous	200	
Pulpwood, coniferous and non-coniferous	31500	
Pulpwood, coniferous		
Pulpwood, non-coniferous		
Total	67400	445500

Appendix Table 2: Net roundwood harvest in 1000 m³fub. Swedish harvest data are from SFA (2018a) and information on ROW harvest is from FAO Statistics (2018).

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	3993	4896	25	4114	3243	1250
East	3341	4734	23	3641	2176	1277
West	3136	1354	21	2461	1922	731
South	11338	2908	152	6886	2350	1448
ROW	140158	34088	54229	74963	56718	85344

Appendix Table 3: Observed roundwood harvest, by roundwood type and tree species (1000 m³fub). The data is processed and built upon the raw data presented in Appendix Table 2. Tree species and regional disaggregation are calculated based on SLU (2018) and Carlsson (2011). Exogenous supply is added or subtracted according to Appendix Table 4.

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North					2059	
East						
West		0			0	
South						
ROW	14338	11400	-10000	13677	10978	-41500

Appendix Table 4: Exogenous supply added to the model (1000 m³fub). The production levels of forest industry products are multiplied with the IO-coefficients, which gives the required input. Production without (or excessive) feedstock coverage (harvest and imports) is included as exogenously supply and presented above.

b) Observed final product output

	SpruceSawn	PineSawn	NonConSawn
North	2 157	2 454	2
East	1655	2561	21
West	1291	727	8
South	5388	1778	66
ROW	75714	23210	2064

Appendix Table 5: Production of sawnwood in 1000 m^3. Swedish regional are data from SDC (2017) . ROW production is the difference between world production and production in Sweden. ROW NonConSawn is from FAO Statistics (2018). Aggregated coniferous sawnwood data are from FAO Statistics (2018), and was in a first step disaggregated into SpruceSawn and PineSawn based on the proportions provided in Carlsson (2011).

	MechPulp	ChemPulp	RecoveredPulp
North	514	2683	314
East	1098	1759	0
West	475	1864	135
South	887	1891	403
ROW	25416	138983	229502

Appendix Table 6: Production of pulp in 1000 tons. Data for mechPulp and ChemPulp are drawn from SDC (2017). Data on RecoveredPulp are from SFI (2018). Firm level data have been assigned manually to the regions as defined in Figure 3. ROW data are from FAO Statistics (2018).

	Fiberboard	Particle board	Plywood board
Sweden	78	543	10
ROW	5671	31945	4559

Appendix Table 7: Production of wood boards, in 1000 m^3. The production of fiberboard, particleboard and plywood in Sweden has decreased significantly during the past ten years. In 2016, the total production amounted to 631 thousand m3, which can be compared to 845 thousand m3 in 2008 and 1626 thousand m3 1980. Due to the very few companies left in the market and to avoid firm identification, the regional data are confidential and will not be presented here, but exist in the model. The data for 2016 have been obtained through private e-mail correspondence with the industry organization The Swedish Federation of Wood and Furniture. The information on ROW production is from FAO Statistics (2018). Fiberboard include hardboard and "other fiberboard".

	NewsPaper	PrintPaper	OtherPaper
North	20	1165	2161
East	0	15	2142
West	0	15	1499
South	790	2060	1713
ROW	5438	24576	50940

Appendix Table 8: Production of paper in 1000 tons. Regional data for Newsprint and Print paper are from information about plant capacity obtained via private e-mail correspondence. The regional data for OtherPaper are approximate estimations based on FAO Statistics (2018) and private e-mail correspondence.

	Wood chips	Sawdust	Bark
North	21	371	30
East	37	643	51
West	15	259	21
South	64	1128	90
ROW	861	15550	806

Appendix Table 9: Pellets production by feedstock in 1000 tons. Regional pellets production is obtained from the annual pellets map compiled by BET (2017). The feedstock shares (wood chips, sawdust and bark) are not available data. According to The Swedish Pellets Association, almost all pellets produced in Sweden originates from sawdust, but not all (e-mail correspondence, May 2018). The total pellets quantity is disaggregated into raw materials based on the raw material proportions presented in Carlsson (2011). Total ROW production is from IEA Bioenergy (2017) and disaggregated into originating feedstock based on the following proportions: wood chips 5 %, sawdust 90 %, and bark 5 %.

c) Prices

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	416	438	447	276	273	274
East	468	449	447	257	239	255
West	468	449	447	257	239	271
South	582	497	447	278	268	329
ROW	482	397	347	178	168	329

Appendix Table 10: Roundwood prices in SEK/m^3fub, before price calibration. Price data on wood type (sawlog or pulpwood) and tree species (except NonConLog) are from (SFA, 2018b). The price of NonConLog is approximated with the Finnish price for NonConLog price (exchange rate SEK/EURO 9.5*). The basic disaggregation into regions is based on the regional disaggregated by (SFA, 2018b) and then manually adjusted (with approximation) to the regions presented in Figure 3.*

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	487	347	248	235	112	248
East	485	345	293	233	209	246
West	379	337	238	233	220	238
South	385	337	241	133	121	241
ROW	476	233	201	239	117	135

Appendix Table 11: Roundwood prices in SEK/m^3fub, after price calibration.

	SEK/unit
SpruceSawn (m^3)	1797
PineSawn (m^3)	1757
NonConSawn (m^3)	3221
NewsPaper (ton)	4103
PrintPaper (ton)	5809
OtherPaper (ton)	7533
FiberBoard (m^3)	3083
ParticleBoard (m^3)	2582
PlywoodBoard (m^3)	5521

Appendix Table 12: Prices of Prices of final output products. Data on SpruceSawn and PineSawn are from UNECE (2018). Paper product prices and NonConSawn are from export prices from FAO Statistics (2018) divided by exported volume. Exchange rate 8.6 SEK/US$.

	SEK/unit
MechPulp (ton)	3807
ChemPulp (ton)	5258
RecoveredP (ton)	1430
Pellets (ton)	2705

Appendix Table 13: Prices of intermediate products. The pellet price is from SPA (2017). The price of MechPulp, ChemPulp and RecoveredP are from FAO Statistics (2018) export prices divided by exported volume. Exchange rate 8.6 SEK/US$.

	SEK/unit
Chips (m^3)	353
Dust (m^3)	297
Bark (m^3)	248
Black liquor (MWh)	273

Appendix Table 14: Prices of industry by-products in SEK/unit from SCB (2017). The price of Black liquor is assumed to equal the price for densified wood fuels. Wood fuel prices at thermal power stations, using a conversion factors of 1.608 MWh/m^3 of bark and 1.920 MWh/m^3 of wood chips and sawdust.

d) Heat and power

	Wood chips	Sawdust	Total
North (TWh)	1,04	0,83	1,86
East (TWh)	0,65	0,20	0,65
West (TWh)	0,30	0,02	0,32
South (TWh)	2,72	0,94	3,66
Tot. use in district heating sector (TWh)[1]	4,70	1,95	6,69
Reference use in industries (TWh)[2]	8,70	0,88	9,56
Total reference use (TWh)	13.40	2.85	15.02
Total reference use[3] (million m^3)	7.00	1.49	7.82

Appendix Table 15: Sweden's energy demand for chips and sawdust. The total use in district heating sector (TWh) is derived from Swedenergy (2016). Reference use in industries (TWh) is derived from SDC (2017). A conversion factor of 1.92 MWh/m3f is used for both woodchips and sawdust to calculate the *total reference use (million m^3).*

Region	Harv res.	Wood chips	Saw dust	Bark	Black liquor	**Tot. by-prod**	Pellets Large	Pellets Small	**Tot. Pellets**	Fossil Large	Fossil Small	**Tot. Fossil**	Total
North	0,75	2,09	0,22	2,57	13,19	18,81	0,27	0,35	0,62	8,7	0,43	9,13	28,56
East	2,59	7,77	1,19	6,04	8,65	26,24	1,39	0,62	2,01	1,8	1,6	3,4	31,65
West	1,77	2,07	0,36	1,18	9,16	14,54	0,15	0,70	0,85	1,4	1,16	2,56	17,95
South	4,13	6,95	1,08	5,24	9,3	26,7	0,51	1,06	1,57	32,6	1,3	33,9	62,17
Tot	9,24	18,88	2,85	15,02	40,3	86,29	2,32	2,727	5,05	44,5	4,49	48,99	140,33
Row	0	0	0	80	180	260	0	42	42	640	71	711	1113

Appendix Table 16: Feedstock composition in the HP sector (TWh) for large users (district heating plants and forest industries) and small users (households and small industries). Regional HP produced from forest biomass and fossil fuels in Swedish district heating plants is compiled from Swedenergy (2016). The energy use in forest industries is derived from Statistics Sweden (SCB, 2018b) and regionally divided according to the shares presented in Carlsson (2011). The use of harvesting residues are approximate calculations based on by-product data from Swedenergy (2016). The use of woodchips and sawdust in Sweden are derived in Appendix Table 15, to which 5.45 TWh has been added from other industries derived from SCB (2018b). Domestic bark and liquor are by-products from sawnwood and paper production, and are derived from observed production multiplied with the generated by-product volumes according to the input-output tables presented in Carlsson (2011). All liquor and bark are assumed to be consumed in the same region as it is produced. ROW use of bark and liquor is arbitrary chosen. Swedish Pellets Large and Pellets Small are derived from SCB (2018b), BET (2017) and The Swedish Pellet Association (2017). ROW use of Pellets Small is arbitrarily chosen. Small households' use of firewood for heating is not included.

	Population	Population share
North	880221	8,81%
East	2487848	24,91%
West	2204536	22,07%
South	4416723	44,21%
Sweden, total	9989328	

Appendix Table 17: Regional population density in Sweden in 2016. Municipality population data are obtained from Statistics Sweden (2018).

e) Reference use for forest industry products

1000 m^3	SpruceSawn	PineSawn	NonConSawn
North	221	108	11
East	625	304	30
West	554	269	27
South	1109	539	53
ROW	75714	23210	10095

Appendix Table 18: Reference use of sawnwood in 1000 $m^{3.}$ Reference demand for NonConSawn is an approximate calculation based on net export (FAO Statistics, 2018) minus reference production, assigned to the regions in proportion to the regions' population density (Appendix Table 17). Data on demand for SpruceSawn and PineSawn are only available on national scale. Regional disaggregation is calculated manually in consultation with the Swedish Forest Industries Federation (2018-05-18). Consumption in ROW is the difference between world production FAO Statistics (2018) and the consumption in Sweden. Thus, all produced sawnwood produced is assumed to be consumed.

	FiberBoard (m^3)	ParticleBoard (m^3)	PlywoodBoard (m^3)
North	24	29	13
East	68	83	38
West	60	74	34
South	120	147	67
ROW	63490	31613	4370

Appendix Table 19: Reference use of r wood boards in 1000 m^3. Reference demand for wood board products is based on approximate calculations, in turn based on net-export from FAO Statistics (2018) minus reference production, assigned to the regions in proportion to the regions' population density (Table A17). Wood board consumption in ROW (FAO Statistics, 2018) equals the difference between world production and consumption in Sweden. Thus, all produced wood board products produced in the world are assumed to be consumed in the world.

1000 ton	NewsPaper	PrintPaper	OtherPaper
North	8	74	173
East	24	209	488
West	21	186	432
South	42	372	866
ROW	6153	26991	56497

Appendix Table 20: Reference use of paper products in 1000 tons. Reference demand for paper products is based on approximate calculations, in turn based on net-export from FAO Statistics (2018) minus reference production, assigned to the regions in proportion to the regions' population density (Table A17). Paper consumption in ROW is the calculated difference between world production (FAO Statistics, 2018) and consumption in Sweden. Thus, all paper produced is assumed to be consumed.

f) Trade

	import	export	net-imports
Pellets (ton)	267977	228316	39661
Wood chips, particles and residues (m^3)	2487478	695372	1792106

Appendix Table 21: Trade of pellets and forest industry by-products (wood chips, particles and residues) between Sweden and ROW. Source: FAO Statistics (2018)

	Reference data	Calibrated data
Coniferous roundwood	4,34	4,47
Non coniferous roundwood	2,46	2,15

Appendix Table 22: Imports of roundwood, in m3f millions. Column two is reference data of imports from FAO Statistics (2018), and column three is the model's calibrated data for imports (based on the reference data).

Paper II

Second Generation Biofuels and the Competition for Forest Raw Materials: A Partial Equilibrium Analysis of Sweden

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Abstract

In order to reach the renewable energy policy targets in the transport sector, biofuels from forest raw materials (e.g., harvesting residues) can play an important role. However, these raw materials are currently used in the heat and power (HP) sector and in the traditional forest industries. It is essential to understand how these sectors would be affected by an increased penetration of second generation (2G) biofuels. This study investigates price development and resource allocation in the Swedish forest raw materials market in the presence of 5-30 TWh of 2G biofuel production. Sweden is an interesting case study due to its well-developed forest industries and mature district heating sector, something which makes it a suitable country for future 2G biofuel production. A national partial equilibrium model of the forest raw materials market is extended with a 2G biofuel module to address the impacts of such production. The simulation results show increasing forest industry by-product (e.g. sawdust) prices, thus suggesting that the 2G biofuel targets lead to increased raw material competition. The higher feedstock prices make the HP sector less profitable, but very meagre evidence of substitution of fossil fuels for by-products is found. In this sector, there is instead an increased use of harvesting residues. Fiberboard and particleboard production ceases entirely due to increased input prices. There is also evidence of synergy effects between the sawmill sector and the use of forest raw materials in the HP sector. Higher by-product prices spur sawmills to produce more sawnwood, something that in turn induces forest owners to increase harvest levels. Already in the 5 TWh Bio-SNG scenario, there is an increase in the harvest level, suggesting that the by-product effect kicks in from start.

Keywords: second generation biofuels, partial equilibrium model, forest raw materials, by-product

1. Introduction

One of the key strategies to combat climate change is to replace fossil fuels with renewable energy sources in the transport sector. During the recent decade, the share of biofuels in the European Union (EU) transport sector has increased from 8.5% (in 2004) to 17% (in 2016) (Eurostat, 2018). However, at present almost all transport fuel is produced from crops grown on agricultural land, so called first generation (1G) biofuels. The resulting competition with food production is deemed to be worrisome, not least because of possible threats to global food security (Lotze-Campen et al., 2014). For this reason, the global community is currently searching for sustainable biofuel alternatives produced from lignocellulosic biomass and other non-edible feedstocks, so-called second generation (or advanced or next-generation) biofuels, hereafter referred to as 2G biofuels.[1] While an increased use of such biofuels will lead to less intense conflicts with food production, it could instead fuel competition for the forest raw materials. This paper addresses the question of how a policy-driven increase in the demand for such biofuels may affect the competition for raw materials among the various users of forest resources.

On June 14, 2018, negotiators from the European Commission, the European Parliament and the European Council reached a deal on the proposed revised Renewable Energy Directive (REDII), which sets new targets for renewables in the EU. The proposed Directive stipulates that at least 14% of the transportation fuel must come from renewable sources by the year 2030, but only 7% can come from 1G biofuels. The share of 2G biofuels and biogas must be at least 1% in 2025 and at least 3.5% in 2030 (EU 10308/18, 2018). Forest industry by-products and harvesting residues are considered sustainable, and they therefore constitute viable feedstocks for 2G biofuel production (European Parlament, 2017). However, these resources are scarce, and are currently used in the traditional forest industries as well as in heat and power (HP) production. For the above reasons, 2G biofuel production may be associated with sharply increasing marginal costs. In other words, strong policy incentives for the domestic production of 2G biofuels may have profound impacts on feedstock prices, and in turn lead to a

[1] Other sustainable biofuels are so called third generation biofuels (produced from e.g. algae), and fourth generation biofuels (e.g. electrofuels) that are not produced from biomass (Aro, 2016; Liew et al. 2014). Third and fourth generation biofuels are not further addressed in this paper since the focus is on forest biomass markets.

substantial re-allocation of forest biomass across the existing and the new sectors using such feedstock.

The purpose of this paper is to investigate price formation and resource allocation in a domestic forest biomass market in the presence of increased 2G biofuel production and demand. This research focus is motivated for three reasons: (1) feedstock costs constitute a substantial share of the total cost of biofuel production (Gnansounou and Dauriat, 2010; Levasseur et al., 2017; Millinger et al., 2017); (2) it reveals how new raw material prices could affect forest industries' production, which in turn affects the by-product supplies; and (3) it indicates whether resources tend to be drawn away from the more mature bioenergy-using HP sector. For these reasons, feedstock price formation is crucial information in order to evaluate the competitiveness of various biofuel production alternatives. By acknowledging the potential market effects from introducing 2G biofuels (e.g. in the transport sector), the results from this paper can also lead to more informed policy decision-making.

In the presence of an increased demand for forest biomass, at least two market effects can be expected: a *competition effect* and a *by-product effect* (Lauri et al., 2017). The competition effect is the increased competition for raw materials under a constrained biomass supply. This causes feedstock prices to increase, but typically by different magnitudes depending on the supply situation for various feedstocks and the willingness-to-pay of various users. The by-product effect refers to the synergy effect between the forest industries producing by-products and sectors demanding by-products, e.g., plants producing heat or 2G biofuels. When such plants demand more by-products (wood chips, sawdust etc.), the prices of by-products increase, in turn generating higher returns to the plant owners supplying these. In addition, this could give an incentive to increase the production of the main product, something that in turn generates more by-products. In other words, whereas the competition effect leads to feedstock price increases, the by-product effect can mitigate such a price rise by inducing an increase in the supply of by-products.

In the paper, we investigate these concepts in the empirical context of the Swedish forest raw material markets. Sweden is an interesting case study for several reasons. Productive forest land accounts for 57% of Sweden's land area; the country has a well-developed forest industry sector as well as a mature bioenergy dependent HP sector. The technological know-how together with the existing infrastructure also make Sweden a suitable candidate for increased 2G biofuel production using lignocellulosic biomass (Mola-Yudego et al., 2017; Mustapha et al., 2017a).

In 2016, total demand for transport fuel in Sweden amounted to 92.4 TWh (SEA, 2017). As much as 16% (16.9 TWh) originated from biomass. However, the majority of the biofuels were imported 1G biofuels.[2] In Sweden, there is a strong political will to increase the domestic production of sustainable transport biofuels (Swedish Government, 2016, 2017).

In order to assess the forest raw materials market effects under the introduction of increased 2G biofuel production and demand, scenarios of 5-30 TW 2G biofuel production are assessed in a partial equilibrium forest sector model. Specifically, the so-called Swedish Forest Sector Trade Model II (SFSTMII) is used. In the paper, this model is updated to the reference year 2016, and extended with a 2G biofuel module, including domestic demand and production of such fuels.

The by-products generated in the Swedish forest industries are to a large extent used in the pulp and paper industry and in the HP sector. Since forest biomass is a scarce resource, introducing 2G biofuel production in Sweden is likely to affect the domestic forest biomass markets and thus the other sectors demanding biomass. Additional demand for biomass can lead to increased or decreased feedstock prices, depending on resource allocation, and the relative magnitudes of the competition effect versus the by-product effect. The outcome depends on the relative price changes of the various feedstocks, which together with the agents' demand functions and technologies determine the feedstock allocation. By identifying changes in resource allocation within and between sectors, as well changes in terms of domestic production and international trade, it will be possible to learn more about the market effects of implementing 2G biofuel production targets.

The remainder of the study is organized as follows. An overview of the literature is provided in Section 2. The modeling approach, including the original model, the model extensions, and the scenarios, are outlined in Section 3. The simulated scenario results addressing the 5-30 TWh of 2G biofuel demand targets in the Swedish biomass market, including a sensitivity analysis on import levels, are presented in Section 4. Finally, Section 5 provides a discussion of the results,

[2] In 2016, Hydrotreated Vegetable Oil (HVO) accounted for 68% (mainly produced from vegetable and palm oil). Ethanol accounted for 7% of total transport biofuel use, out of which 97% originated from edible crops. Raw tall oil, a 2G biofuel, accounted for 7% of total biofuel use. The remaining 18% of biofuels originate from "other" 1G biofuel feedstocks (SEA 2017).

while Section 6 summarizes the main conclusions from the analysis, and outlines some important avenues for future research.

2. Overview of the literature

The majority of previous studies investigating market effects from introducing a biofuel target focuses on the competition for land (e.g. Havlik et al., 2011; Thompson et al., 2010). A 2G biofuel target removes the obstacle of land use competition, this since land use does not change with increased production. The main obstacle to increased 2G biofuel production instead relates to production costs, which generally are higher than those for 1G biofuels. The total production costs for 2G biofuels are in turn largely driven by feedstock prices (Festel et al., 2014; Havlik et al., 2011). In an extensive report of 2G biofuel production costs, Landälv and Waldheim (2017) conclude that the single most important variable, which influences the overall production cost, is the feedstock price. For instance, in HVO production, feedstock costs account for 60-80 % of the total production costs. The feedstock costs for bio-diesel produced from forest biomass is estimated to account for more than 70% of the future total production costs (in 2020) (Festel et al., 2014). Whereas investment (capital) costs typically decrease with increased units produced (due to scale economies, learning-by-doing effects, etc.), the share of feedstock costs is also likely to increase with increased production (e.g. Gnansounou and Dauriat (2010). In other words, the profitability of 2G biofuel production is heavily dependent on feedstock prices, and this makes feedstock price formation particularly relevant to study.

Söderholm and Lundmark (2009) discuss some conceptual issues concerning the competition for forest raw materials; price formation and resource allocation. They distinguish between three separate product categories: main products, co-products, and by-products. Although all products are produced simultaneously, their market characteristics differ. The market for the main product is the key determinant of production levels. Yet, if co-products are required to make the production for the main product economical, the market for these co-products will influence production decisions. By-products are produced in association with the main product and co-products, but they do not influence production levels since they are spill-over products and will be produced regardless of its market price. Contrary to the definitions introduced by Söderholm and Lundmark (2009), the modeling setting in this paper will allow by-products to influence the levels of main products produced, i.e., essentially implying that products that have been by-products may become co-products. Specifically, the underlying production functions will include by-products and the endogenously determined market prices for these. Whether by-product prices will affect the main product levels or not is therefore an empirical question. This is further discussed in Section 5.2.

Lauri et al. (2017) investigate the forest biomass market implications of reaching the 2 °C global climate target. They find that higher biomass demand for energy can be achieved without significant distortions to the forest biomass markets. This result refers to the by-product effect, i.e., increased use of forest biomass for energy increases the demand for sawmills' by-products. This makes the sawmill industry more profitable, and it thus compensates for the cost effect of increased competition over raw materials. Lauri et al. (2017) describe their finding as an inverted U-shaped function effect where woody biomass material use depends on the trade-off between the by-product and the competition effect, respectively. Thus, similar to the present study, Lauri et al. (2017) allow for the by-products to influence the production levels of the main production.

When analyzing an increased EU demand for wood pellets, Jonsson and Rinaldi (2017) find both by-product effects and increased competition between wood-based products and wood pellets. They find that sawmills benefit from an increase in wood pellets demand. Whereas both Lauri et al. (2017) and Jonsson and Rinaldi (2017) assess the forest biomass market from an international perspective, the present study assesses the effects of EU policies on a domestic market. For our purposes, the domestic forest biomass market is disaggregated into a range of main forest products, intermediate products and by-products. The empirical focus on a single country thus permits a more in-depth assessment of the various links between the sectors using forest raw materials.

In a study about the Norwegian forest biomass markets, Trømborg et al. (2013) investigate how 2G biofuels made from lignocellulosic biomass could affect the competitiveness of bioheat generation. Similar to the present study, they use a national spatial partial equilibrium forest model. They find that the pulp production shrinks and sawnwood production increases in the presence of a higher demand for 2G biofuels. Moreover, the bio-heat production is reduced by 5-20 percent depending on the 2G biofuel production levels. The latter is an interesting result; if bioheat is reduced in favor of 2G biofuel production, the environmental benefits may be dubious. Sweden and Norway and their forest biomass markets are however different in several respects; Sweden has more than three times the amount of productive forest land (SLU, 2018; SSB, 2017), a larger forest industry sector and a mature bioenergy-dependent HP sector. This suggests that Sweden is likely to have a comparative advantage in 2G biofuel production, while this may be less likely for Norway (Mustapha et al., 2017b).

In order to account for spatial differences in forest supplies, Ouraich et al. (2018) develop a geographically explicit price determination model of forest raw materials. An exogenous demand is defined for forest raw materials. Demand is satisfied with supply from the region(s) with the lowest supply cost (based on availability and transport costs). Ouraich et al. (2018) apply this model to Sweden, and assess forest raw material prices under different levels of 2G biofuel demand. Following an increase in 2G production of 30 TWh, almost no price effects in the domestic raw material market are detected. This is explained with the high model resolution, which enables the model to choose feedstock more efficiently. The model does however not consider market interactions between sectors competing for forest raw materials. Leaving out the market interactions could potentially lead to both an under and an overestimate of feedstock prices. Even a small price increase for one feedstock can cause an industry to substitute another feedstock for this feedstock; this will push up the price of the alternative feedstock and induce a chain reaction of price changes and altered resource allocations.

In order to assess price formation and the competition for raw materials, a model that includes the various sectors demanding the respective feedstocks is warranted. Carlsson (2011) employs the so-called SFSTMII model with reference year 2008 to investigate the effects of introducing more ambitious bioenergy demand targets in the HP sector in Sweden (5-25 TWh). He finds increasing raw material prices, and that increased demand in the bioenergy sector is satisfied with increased use of harvesting residues and pulpwood. The increased demand for pulpwood causes the pulpwood price to increase to the price levels of sawlogs. When that happens, also sawlogs are used as feedstock in the HP sector. Because additional pulpwood was imported (i.e., no additional supply of harvesting residues), and no increased use of by-products was found, no by-product effects were detected by Carlsson (2011).

To conclude, previous studies have often focused on either 1G biofuels and/or countries as a group, while the present paper focus on 2G biofuels and one domestic market. Moreover, this study accounts for market effects, i.e., interactions between sectors and industries via prices. Unlike Carlsson (2011), and in line with the so-called waste hierarchy established in Directive 2008/98/EC, and re-established in the proposed REDII directive (EU 10308/18, 2018), this paper does not allow chipped pulpwood as a feedstock for energy conversion counted towards the renewable energy targets. Finally, while the present study has a national perspective, similar to the Trømborg et al. (2013) study, it assesses the case of Sweden, which is considered to have a great potential for future production of 2G biofuels.

3. Material and method

Our primary interest is to analyze the raw material competition in the Swedish forest biomass market in the presence of 2G biofuel demand targets. A number of scenarios are investigated in a partial equilibrium modeling setting, in which the Swedish sawmill, pulp and paper, HP and 2G biofuel sectors, are described. The demand target scenarios vary between 5 and 30 TWh of 2G biofuels, and are all compared to the baseline year 2016.

3.1. Modeling approach and data

Lestander (2011) developed the Swedish Forest Sector Trade Model (SFSTM), which is a static partial equilibrium model including forest harvest, forest industry production and the demand for various forest industry products in Sweden. It can be employed to analyze the competition for forest raw materials among sectors in the traditional forest industry (e.g., sawmills, pulp and paper plants). In this model, Sweden is divided into four geographical regions. These domestic regions trade raw materials and forest industry products with each other, as well as with a region representing the Rest of the World (ROW).[3] ROW is incorporated as a trade partner to the domestic regions in order to reflect international competition for forest biomass and forest industry products. Carlsson (2011) extends the SFSTM model with a bioenergy using HP sector module in order to analyze the welfare effects (i.e., consumer and producer surplus) from an increased bioenergy demand in this sector. Carlsson's model is here referred to as the SFSTMII model.

The SFSTM as well as the SFSTM II models consist of two sub-models: one trade cost model that calibrates prices and feedstock allocation to a reference year, and one model that can be used to simulate prices and feedstock allocations under various scenarios. The trade cost model is a Takayama-Judge (1964) type spatial partial equilibrium model, which builds upon Samuelson's (1952) spatial equilibrium theory. Specifically, the sum of consumer and producer

[3] In the model, ROW includes the EU Member States and Norway.

surplus is maximized, and the objective function solution provides market equilibrium prices and quantities under free competition as shown by Samuelson's (1952).

In the Swedish forest model, all products can be traded except HP energy and black liquor (a by-product from pulp mills), which are assumed to be consumed in the same region as they are produced. In the second sub-model, net social welfare is calculated as the sum of the areas under each demand curve minus production costs in the production sectors, including the sum of transportation costs resulting from trade between regions. Suppliers maximize their profits (producer surplus) and consumers maximize their net benefits (consumer surplus). The sectors relying on the forest raw materials are assumed to act in a market characterized by perfect competition. The maximization of producer and consumer surplus provides the equilibrium resource allocation and prices. The modeling structure builds on the same structure of demand, supply and trade as in the Global Trade Model (GTM) (Kallio, 1987) and the EFI-GTM (Kallio et al., 2004) models, as well as in the Norwegian forest sector model NTMII (Bolkesjø, 2004).

The demands for forest industry products (sawnwood, paper and board products) and HP energy are represented with demand functions. Sawlogs, pulpwood and harvesting residues are supplied by forest owners. Production, feedstock allocation within and between sectors, as well as price formation, are endogenously determined. For a detailed description of the equations in the model, see Carlsson (2011). In order to investigate the effect of increased 2G biofuel demand on the existing HP sector and the forest industries, this study extends SFSTMII by implementing a 2G biofuel module, i.e., exogenous demand for 2G biofuels and endogenous production technologies for such fuels using forest biomass as feedstock. How this extension was pursued is discussed in detail in the next sub-section.

Figure 1 provides an overview of SFSTMII, including the new module. The model consists of three parts: the upper box (part 1, Raw materials) depicts forest owners' supply of roundwood and harvesting residues. The middle box (part 2, Activities) shows the part where all the production and conversion processes reside. The underlying production functions are of a Leontief structure, and are thus represented with fixed input-output (IO) coefficients.[4] The IO-approach is suitable for modeling sectors with agents entangled via many productions paths, and it has been commonly used in the forest sector modeling literature (see Sjølie et al., 2015 for a review of forest sector modeling approaches). Since the IO-coefficients are fixed sets

[4] All IO-coefficients (except those for 2G biofuel production) are from Carlsson (2011).

(technology and feedstock), there exist no continuous substitution possibilities between various feedstocks. Nevertheless, by including several IO-coefficients with different feedstocks for one technology, substitution between feedstocks is implicitly included and some constrained substitution effects can be analyzed. The boxes to the left in part 2 represent forest industry production, e.g., the production of sawnwood demands sawlogs from the forest owners, and then supplies sawnwood to end-users as well as by-products (e.g., wood chips, sawdust and bark) to the pellets industry, the HP sector and the 2G biofuel sector. The upper box to the right in part 2 (Tech 1, Tech 2, …, etc.) shows the IO-activities (i.e., IO-coefficients of conversion technologies using different feedstocks) to produce HP. The lower box to the right in part 2, represents the IO-activities to produce 2G biofuels, here one technology (Bio-SNG) in combination with different feedstock options.

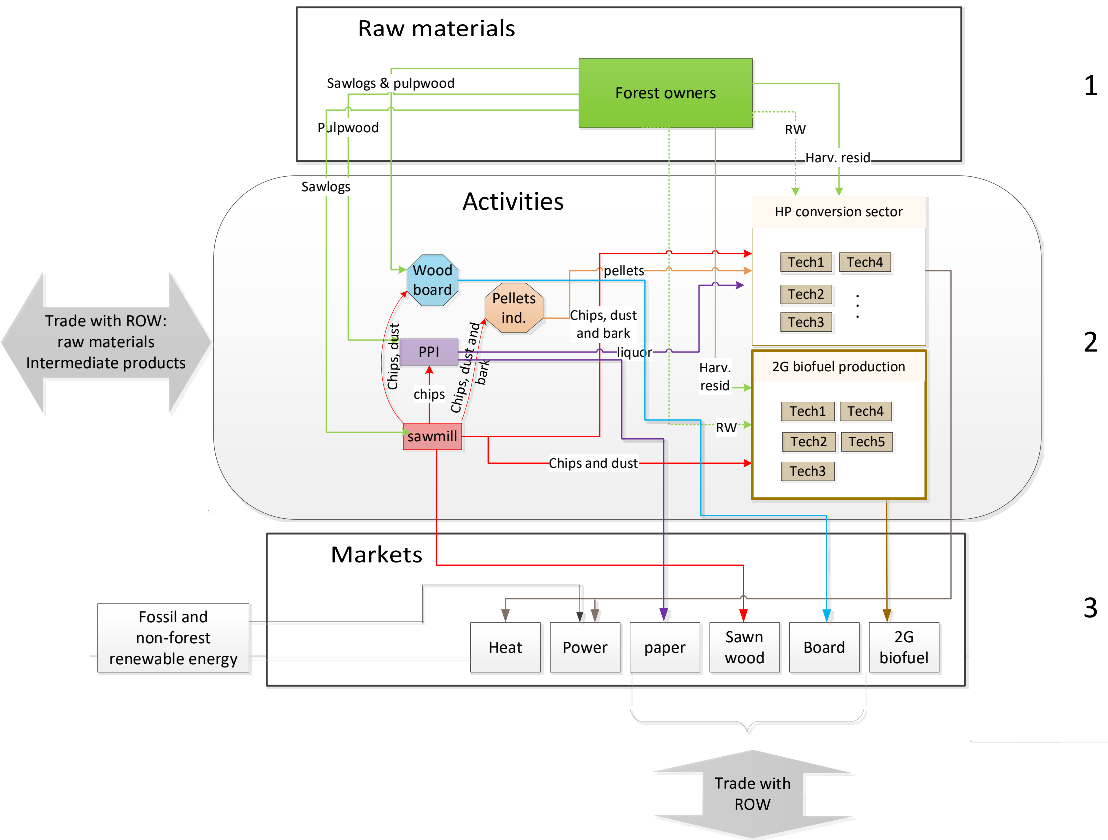

Figure 1: The Swedish Forest Sector Trade Model with 2G biofuel production.

The bottom box (part 3, Markets) in Figure 1 depicts the demand for final products: HP, 2G biofuels, and forest industry products such as paper and board products and sawnwood. The model is driven by the demand for final products, which in turn leads to an endogenous demand for raw materials, intermediate products and by-products.

The demand functions for HP and forest industry products are defined as follows:

$$D_{i,f} = \widehat{D}_{i,f} \left(\frac{P_{i,f}}{\widehat{P}_{i,f}}\right)^{\varepsilon} \tag{1}$$

where D is the endogenously determined quantity demanded. The index i corresponds to the region in which the demand takes place, whereas the index f corresponds to which product is demanded (e.g. HP and sawnwood). The parameter $\widehat{D}$ refers to the reference demand level (observed demand for the reference year), and is used as a start value in the calibration model. P is the endogenously determined price and varies with feedstock costs. The parameter ε is the own-price elasticity of demand. For forest industry products, ε ranges between -0.60 and -0.17. The corresponding demand elasticity for HP is -0.3. The demand for HP can be satisfied with either fossil fuels or bioenergy.

Finally, the model can trade with ROW (indicated with large grey arrows in Figure 1). The model will choose to import a product if the import price is lower than domestic production costs plus transport costs (given that demand exceeds supply). If the domestic consumer market is saturated for a product, and domestic production is cost competitive with ROW production, then the product will be exported to the ROW. ROW Baseline product prices are, similarly to the remainder of the model, calibrated to 2016 data on the use and production of products. Since the Swedish market is relatively small from an international perspective, ROW prices are assumed to not be affected by any changes in the Swedish market. The model is programmed in the General Algebraic Modeling System (GAMS), and the so-called CONOPT solver has been used both for the transportation cost minimization problem and the welfare maximization problem.

3.2. Implementing the second-generation biofuel technology module

Various 2G biofuels differ in terms of properties, production costs, environmental performance and accessibility. Furthermore, the same biofuel can vary substantially in performance and cost performance depending on the characteristics of biofuel production processes, e.g. plant size, technologies, investment time frame. In addition to the disparate biorefinery processes and fuel properties, techno-economic estimates of the production costs of 2G biofuels tend to differ substantially due to methodological differences (e.g. assumed interest rates, system boundary assumptions, etc.). This makes it arduous to compare production costs across various studies (Carriquiry et al., 2011; Gnansounou and Dauriat, 2010; Haarlemmer et al., 2012). In an extensive review of 2G biofuel production costs, Landälv and Waldheim (2017) identify a cost range of 50-140 EUR/MWh. Fisher-Tropsch liquids production costs range between 90 and 125 EUR/MWh, Biomethane, methanol and DME between 56 and 91 EUR/MWh, HVO between 50 and 90 EUR/MWh, and cellulosic ethanol between 85 and 103 EUR/MWh. The above differences originate from assumptions regarding the feedstock costs, technology matureness, installation costs and external factors.

In order to keep this study as transparent as possible, only one type of 2G biofuel is included, represented with one biomass-to-yield conversion rate and one investment cost for capacity expansion. Specifically, 2G biofuel is exemplified with biobased synthetic natural gas (Bio-SNG). The techno-economic potentials of Bio-SNG have been verified in many studies (e.g. Gassner and Marechal, 2012; Gustavsson and Hulteberg, 2016; Pettersson et al., 2015). It is impossible to predict which 2G biofuels that will become successful in the market. Bio-SNG is used as the example in this paper due to its great flexibility; both in terms of feedstocks use, and the upgrading possibilities to several different liquid 2G biofuels (e.g. diesel and ethanol). Following Pettersson et al. (2018), we assume a biomass-to-fuel yield of 70% on an energy basis. For the IO-coefficient specification, four feedstocks are available for production in five fixed proportions: 100 % chips, 100 % sawdust, 50% chips and 50% sawdust, 100% pellets or 100% harvesting residues. The respective feedstocks have different energy contents. Table 1 (third column) shows how much of each feedstock is required to produce one MWh of Bio-SNG. The Bio-SNG is assumed to be produced in stand-alone plants.

Feedstocks (ton)	**calorific value GJ/ton**	**Ton feedstock for 1 MWh Bio-SNG**
Chips	16[a]	0.298
Sawdust	16[a]	0.298
Chips/sawdust	16[a]	0.298
Pellets	17[b]	0.275
Harvesting residues	12[c]	0.387

Table 1: Feedstocks that can be used to produce Bio-SNG in the model. Column two presents the feedstocks' calorific values. These values are from EECA (2017)[a], (Whittaker et al. (2011))[b] and Forest Research (2018)[c]. Column three presents how many tons of each feedstock are required to produce one MWh Bio-SNG.

If demand increases, and the plant is not producing at its maximum capacity, production may increase according to the assumed conversion and feedstock costs. If the plant is producing at its maximum capacity and demand increases, plant capacity can be increased with an investment cost of 229 EUR/MWh[5], and an annualized factor of 0.08, which is equivalent to a 5% interest rate and a production plant lifetime of 20 years.

The size of a Bio-SNG plant is determined by the tradeoff between the economies of scale of larger plants, and increased costs for feedstock transportation. In practice, there is always a minimum plant size to make the production profitable. For Bio-SNG produced in Sweden, the smallest capacity has been estimated at around 100-300 MW (Pettersson et al., 2018). However, since the model builds on the use of Leontief production functions, and substitution of feedstock is only expressed indirectly via fixed sets, the model is at risk to choose corner solutions. This may give rise to lock-in effects in the case of minimum plant size. Considering that it is uncertain which, if any, 2G biofuel that will actually be introduced in the market at any significant scale, it is preferable to avoid such lock in effects caused by big discrete steps in investments. For this reason, plant capacity is in this study allowed to increase in incremental steps of only one MWh. Following Pettersson et al. (2018), the operation and maintenance costs are set to 6.2% of the investment cost, i.e., 14 EUR/MWh[6].

The demand for 2G biofuel is modelled in a similar manner as presented for other final products (Equation 1). However the determined quantity is not allowed to vary (i.e., being endogenously determined) due to exogenous demand targets in the scenario analysis. For modeling reasons, all parameters presented in Equation 1 are included also for 2G biofuel demand (i.e., a reference price, quantity produced and an own-price elasticity)[7], but their magnitudes are not expected to affect the quantities produced. Similar to the HP sector, the four Swedish regions are not allowed to trade 2G biofuels with the ROW, i.e., the 2G biofuel targets have to be achieved based on domestic production. Bio-SNG can however be produced and consumed in all four

[5] This is an average estimate of a plant investment between 100 MW and 300 MW presented in Pettersson et al. (2018)

[6] In Carlsson (2011), the operation and maintenance costs (cost for labor, electricity and other) are assumed to be 27 SEK/m3f of feedstock input, an assumption that is consistent with the corresponding operation and maintenance costs assumed in Pettersson (2018).

[7] As no commercial facilities for bio-SNG production were in operation in Sweden in the reference year (2016), an arbitrary low level Bio-SNG production is assumed across all four regions as a proxy for the current state. The reference price of Bio-SNG is approximated with the production cost for the lower level of Bio-SNG production, averaged across feedstocks (67 EUR/MWh), presented in Pettersson et al. (2018). For Bio-SNG, ε is set to being fully own-price inelastic (i.e., vertical).

domestic regions. Before end-use consumers, e.g., households, can buy the 2G biofuel at a gas station, further processing of the fuel is required as well as transportation of the fuel to the gas station. These steps of the value chain are not described in the model, this in order to keep the analysis as general as possible in terms of technologies.

3.3. Data

SFSTM and SFSTMII were calibrated to the year 2008. For the present study, all data have been updated and calibrated to the year 2016. Six categories of roundwood are included: sawn timber and pulpwood, both of which can be produced from three species: spruce, pine and non-coniferous. Harvesting data (m^3f) are from SFA (2017), SFA (2018) and FAO Statistics (2018). Forest industry production output (final and intermediate products), i.e., different kinds of sawnwood (m^3), pulpwood (m^3), paper (ton), fiberboards (ton), and pellets (ton) are from SDC (2017), FAO Statistics (2018), SFI (2018), CEPI (2017), IEA Bioenergy (2017), BET (2017), The Swedish Pellet Association (2017), and the European Pellet Council (2018).

By-product prices are from SCB (2017). No data on harvesting residues are available; instead estimations of quantities harvested (1.716 million Oven Dried Ton (ODT)), available quantities and the price of 818 SEK/ODT, have been drawn from Carlsson (2011). Roundwood prices are from UNECE (2018) and FAO Statistics (2018). According to the reference values, demand for final products is mostly located in south Sweden. The reference levels for HP demand are based on population density data from Statistics Sweden (2018). Feedstock composition in the HP sector (MWh) is gathered from the Swedenergy (2016) and SDC (2017). The fossil fuel price for the energy sector is assumed to be equivalent to the price of heavy oil, which was 6601 SEK/MWh (about 70 EUR/MWh) in the year 2016 (SPBI, 2018).

Due to imperfections in harvesting data (unreported thinning, imprecise weighing, estimations, etc.), and the modeling assumption made to include the EU and Norway to represent ROW[8], shortages of roundwood and forest industry by-products exist in the calibration model. Following Carlsson (2011), an exogenous supply of forest biomass is added to cover up for

[8] Restricting the definition of ROW to the most frequent trade partners prevents the model from generating misleading simulation results based on aggregated forest data, e.g., roundwood from tropical species with other energy contents than those represented in the model (and in Sweden). Thus, all products are assumed homogenous goods, and therefore no Armington elasticities are included to differentiate between products produced in different regions.

these material imbalances.[9] An exogenous supply of 5.5 m^3f millions of pulpwood has been added, which makes total harvest in the country reach 73 million m^3f. Actual net harvest is 74 million m^3f. The last million cubic meter harvest is neither logs nor pulpwood, and it is categorized as “other”. For the ROW, 13 million m^3f of logs and 19 million m^3f of pulpwood are added to the model. No exogenous by-products had to be added to the Swedish market. During the past 10 years, the EU Member States have experienced a substantial increase in the overall imports of wood chips, sawdust, wood pellets, etc., from non-EU countries. Between 2005 and 2015, such imports increased by approximately 270 %, reaching 14 million tons in 2015 (Eurostat, 2018). Net-imports of wood pellets to the EU from non-EU countries increased by 79% between the years 2009 and 2016.[10] Since this development is not reflected in the model, an exogenous supply of by-products has to be added to the ROW; 94 million m3f sawdust and 115 million m3f wood chips were therefore added to the ROW part of the model.

Another explanation to the difference between demand and supply in the ROW is the assumed IO-coefficients, which in the model are assumed the same for all the countries included in the ROW region, but may vary considerably in reality. This causes imbalances in the data. As Carlsson (2011) points out, another alternative to address the shortages in the ROW, would be to adjust the by-product coefficients from sawn goods production in the ROW region. However, doing that would imply differences in the relative competitiveness between Swedish and ROW sawn goods production when the prices of these by-products change. Full tables of exogenous supply assumptions, including tree species, are presented in the Appendix (Table A1).

The inclusion of exogenous supply will affect the resource allocation in the model. Although the numbers come from observed discrepancies, some products can be produced with more than one feedstock, and therefore, the numbers are not necessarily entirely correct. In order to investigate the impacts of the added exogenous feedstocks, a sensitivity analysis was conducted with different proportions of exogenous roundwood species and wood chips/sawdust to cover the material imbalances. The results in the calibration model were shown to be robust to roundwood species but sensitive to the proportions of by-products. In the latter case, if more

[9] Exogenous supply is calculated in a similar manner as in Carlsson (2011): production multiplied with the IO-coefficients gives the required input. In the case of sawnwood, sawnwood production multiplied with the IO-coefficient for sawnwood gives the harvest of sawlogs.

[10] The main suppliers of EU imports were the United States and Canada; much less has been supplied by Russia and other countries (Eurostat, 2018).

wood chips (or sawdust) was added, the price of wood chips decreased and more wood chips (or sawdust) was utilized in the model. This is the expected result; by-products are expected to be more price volatile than roundwood since their own-price elasticities of supply are expected to be low (Söderholm and Lundmark, 2009). More importantly, in the sensitivity analysis, the relative order of the prices of products was shown to be stable across exogenous feedstock levels, and therefore the exogenous supply assumptions should not be expected to introduce any structural biases in the scenario analysis.

3.4. Scenarios

The baseline scenario (Baseline) is simulated using data for the year 2016. The production of manufactured forest products and HP, as well as trade of raw material and products, are simulated. The baseline scenario thus reflects the Swedish forest raw materials market when no large-scale 2G biofuel production and use has yet been implemented.

Import levels of raw materials are constrained to 2016 import levels. Between 2012 and 2016, EU imports of wood pellets from non-EU countries increased by almost 80% (reaching almost 8000 million tons) (Eurostat, 2018), due to increased feedstock demand for pellets in the HP sector. With current policies, this development is expected to continue (Balan et al., 2013), followed by increased competition and increased feedstock prices (Johnston and van Kooten, 2016; Jonsson and Rinaldi, 2017). Thus, it is unrealistic to assume all countries to satisfy increased demand for biomass with increased imports. For this reason, the import levels in the various scenarios are constrained to those observed in 2016. As noted above, the effects of relaxing this import restriction is analyzed in a separate sensitivity analysis (Section 4.2).

The baseline prices of sawdust and bark are lower compared to observed data. Since by-products do not come with a production cost, the lowest price for which trade will occur is the cost for transportation of the by-products. These prices are formed in direct response to demand. Moreover, given that the model does not include every small sector that demands sawdust, the model finds an oversupply of this product, and this makes the price lower compared to observed data. However, the relative price order of sawdust, bark and the other raw materials are identical with observed data.

In addition to the baseline scenario, a number of scenarios that involve various 2G biofuel demand levels are investigated. The future renewable transport fleet is expected to constitute a mix of different 2G and 1G biofuels, and other types of vehicles, not least electric cars.

Moreover, significant efficiency measures to reduce the overall energy demand for transport can also be anticipated. Still, 2G liquid biofuels are expected to be particularly important in greening heavy transports, and the aviation sector (Bessou et al., 2011; EU 10308/18, 2018; Mustapha et al., 2017b). On July 1, 2018, Sweden introduced a so-called biofuel obligation scheme to reduce emissions in the transport sector (similar to countries like Finland, Germany, Brazil and Canada). The Swedish biofuel obligation scheme requires fuel suppliers to reduce carbon dioxide emissions in gasoline and diesel by blending non-renewable fuels with environmentally sustainable biofuels (Hansson et al., 2018; Swedish Government, 2018).

In this study, a range of 2G biofuel production, from 5 to 30 TWh in steps of five representing different future developments, is investigated. This range corresponds to 4-25% of current total fuel demand in the Swedish transport sector (and 5-33% of the road transport fuel demand). In line with the above-mentioned Biofuel obligation scheme, these 2G biofuel targets force the market to consume 2G biofuels. Thus, in the model, these production (and demand) targets are implemented exogenously.

The simulated results will be presented in the following order. First, the model's choice of feedstock used to produce Bio-SNG is outlined – i.e. the triggering factor for all subsequent events. Secondly, since the Bio-SNG industry and the HP sector are competing for the same feedstock, the feedstock composition in the HP sector is assessed. Thirdly, the forest industry sector's production is assessed; this is linked to price changes caused by 2G biofuel production increases and any feedstock composition changes in the HP sector. The range of 5-30 TWh Bio-SNG is investigated and compared to the baseline level (i.e. no Bio-SNG production). Each scenario (5, 10, 15 TWh…) is thus compared individually to the baseline. In addition to the main results presented and discussed, a sensitivity analysis is conducted in which the role of imports of raw materials is assessed.

4. Scenario results

4.1. Results

Figure 2 shows the feedstock composition in Bio-SNG production for the scenarios ranging between 5 and 30 TWh. Raw sawdust is used for low levels of Bio-SNG production, while pellets (mainly processed sawdust, Figure 3) dominates for the larger production levels. Pellets is cheaper to transport than sawdust due to its higher energy content per ton, and comes with an intermediate processing cost. The model's first hand choice is pellets. As a response to the increased demand for pellets in Bio-SNG production (and the constraint on pellets import), domestic pellets production shoot up after 10 TWh of Bio-SNG production (Figure 3). The initial decline is explained by decreased pellets exports due to an increased pellets price in the domestic market. The use of pure sawdust for low levels of Bio-SNG is likely due to the use of locally supplied sawdust (i.e., with low transport costs). The use of sawdust, raw or processed to pellets, is explained by its relatively low price and high energy content (compared to harvesting residues, etc.).

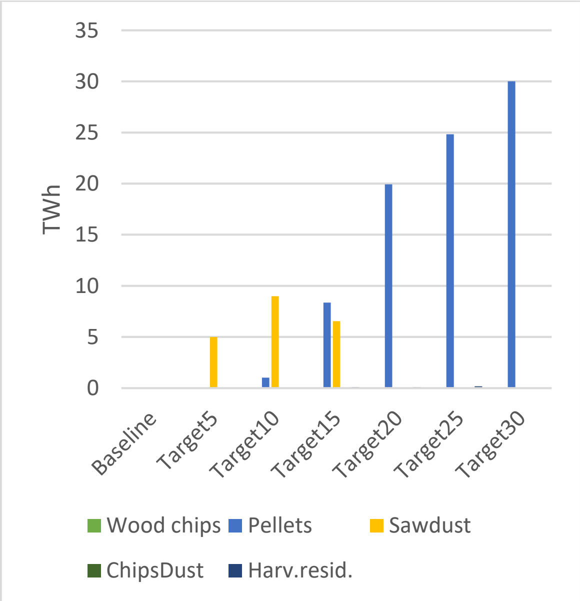

Figure 2: Feedstocks used in the production of 5-30 TWh Bio-SNG.

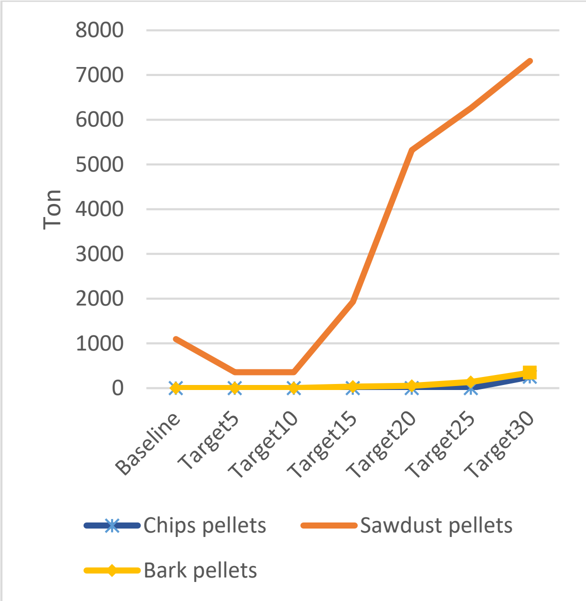

Figure 3: Pellets industry production in ton.

Figure 4 shows the domestic price developments of forest industry by-products and pellets for the different Bio-SNG scenarios. The price formation curve behaves as expected, i.e., it increases slowly in the presence of low demand levels, but becomes steeper when the respective feedstocks are close to reaching their supply constraints. For instance, the supply of the by-products (e.g., sawdust) will be constrained by the production level of the main product (e.g., sawnwood). Figure 4 also provides an indication of how much additional 2G biofuel demand that can be imposed before feedstock prices soar, which in this case seems to be when 20 TWh of Bio-SNG is added to the market demand.

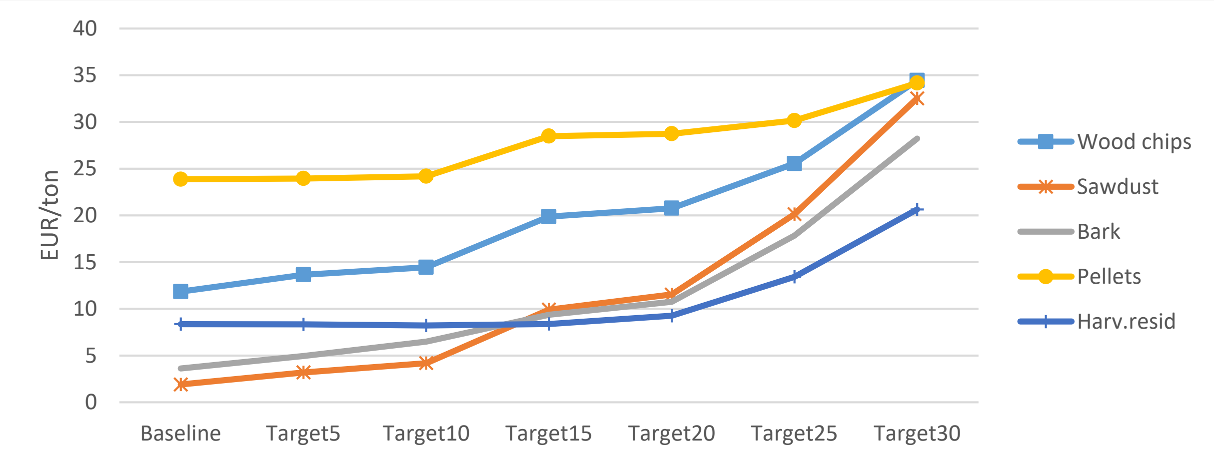

Figure 4 Price development of forest industry by-products and pellets under 5-30 TWh Bio-SNG demand. Wood chips, sawdust, and bark are recalculated to dry ton with the conversion factor 0.29 and using the exchange rate 9.5 SEK/EUR.

Figure 5 shows the feedstock composition in the Swedish HP sector for 0-30 TWh of Bio-SNG production. The total production of HP is assumed to be constant over all scenarios (own-price inelastic demand). However, which feedstock-technology set to satisfy the production is perfectly elastic; i.e., the feedstocks used in the HP sector will vary with feedstock prices. In the HP sector, biomass fuels compete with fossil fuels supplied in unlimited quantities at an exogenously given (world market) price.

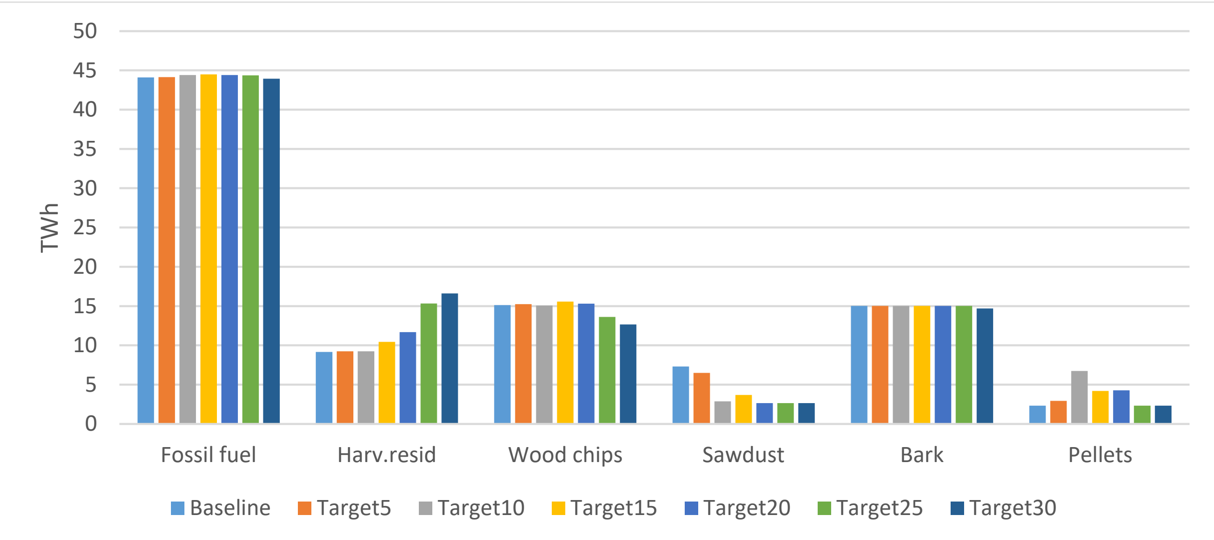

Figure 5: Feedstock composition in the heat and power sector in the presence of 0-30TWh Bio-SNG production. The total amount of heat and power production is constant across scenarios.

As shown in Figure 5, the use of sawdust in Bio-SNG production has consequences for the HP sector's feedstock composition. Sawdust use decreases the most; it decreases already at 5 TWh of Bio-SNG production. The feedstock shortage is covered up by pellets, a development that stops at 10 TWh due to rising by-product prices. In addition, the uses of sawdust and wood chips are cut back due to the price increases. Comparing the 30 TWh Bio-SNG scenario with the baseline, a total feedstock shift of 7.5 TWh is observed in the HP sector; the use of sawdust is reduced by 4.7 TWh. Also the uses of wood chips and bark decrease (by 2.5 TWh and 0.3 TWh, respectively). The resulting feedstock shortage is covered up by an increase in the use of harvesting residues.

A modest up and down in fossil fuel use can be observed in the HP sector. For low levels of Bio-SNG production, the relative price of biomass versus fossil fuels increases. However, once the production of Bio-SNG reaches 15 TWh and beyond, the relative price of biomass-based feedstocks versus fossil fuels decreases due to an increased use of harvesting residues. For levels of Bio-SNG production higher than 15 TWh, harvesting residues are relatively cheaper wood chips, sawdust and pellets. The increased use of harvesting residues is possible due to increased roundwood harvest (see further below). As a result, the total amount of fossil fuels used is slightly lower in the 30 TWh Bio-SNG scenario compared to the baseline. As a response to rising by-product prices, the incentives for sawnwood production increase (the by-product effect). A 26% increase in sawnwood production can be observed (Figure 6).

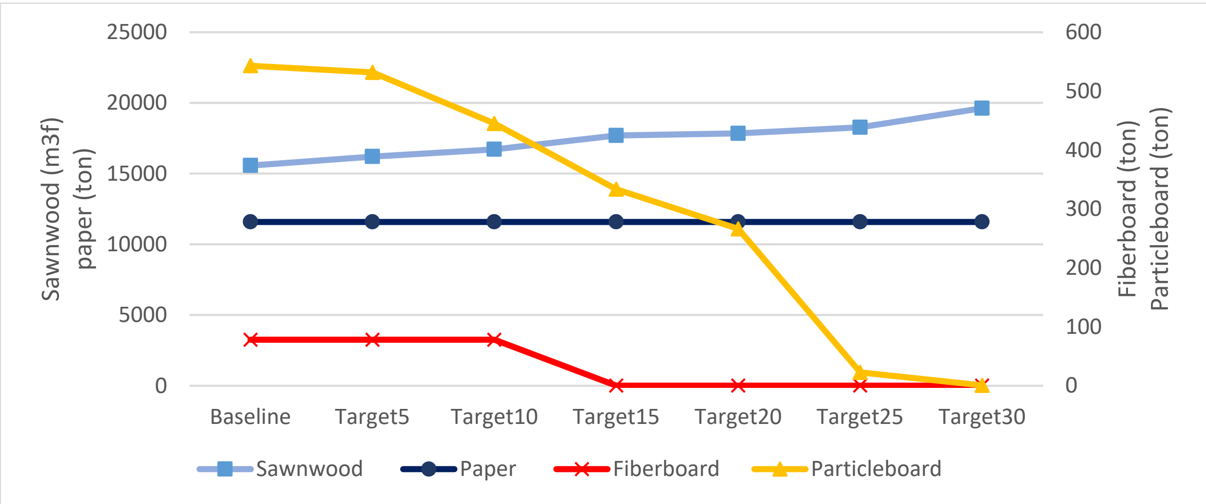

Figure 6: Final product production levels divided into four categories: Sawnwood includes three subgroups: spruce, pine and non-coniferous sawnwood (in m^3f). Paper includes three subgroups: newsprint, print paper and "other paper" (in tons). Sawnwood and paper production levels are shown on the left hand side axis. Fiberboard and Particleboard production levels are shown on the right hand side axis and are in tons.

At the same time, the industries using sawdust as input become less profitable (the competition effect). In the 30 TWh scenario, both the fiberboard and particleboard industries have ceased their production entirely due to the higher sawdust prices and the competition with the pellets industry. This model result is in line with the historical trend of an expanding HP sector using more and more bioenergy at the expense of a declining board industry (FAO Statistics, 2018; SFA, 2014).

With an increased sawnwood production, the demand for sawlogs increases, and is met by an increase in the domestic sawlog harvest (Figure 7). As a result, sawlog prices increase (Figure 8). For 30 TWh of Bio-SNG production, sawlog harvests increase by 8 million m^3f (27 %), reaching 39 million m^3f. As predicted by Di Fulvio et al. (2016), the price tends to increase exponentially with the quantity harvested. The price increase reaches 122 % for 30 TWh of Bio-SNG production. The lower domestic production of particleboard leads to a reduced demand for pulpwood, which in turn implies a 9% decrease in the domestic pulpwood prices (Figure 8). Moreover, with lower domestic pulpwood prices, exports of pulpwood increase and causes pulpwood harvest to grow by 7% (see Figure 7). With increased roundwood harvests, the supply of harvesting residues increases, and this explains the increased use of this feedstock in the HP sector (Figure 4).

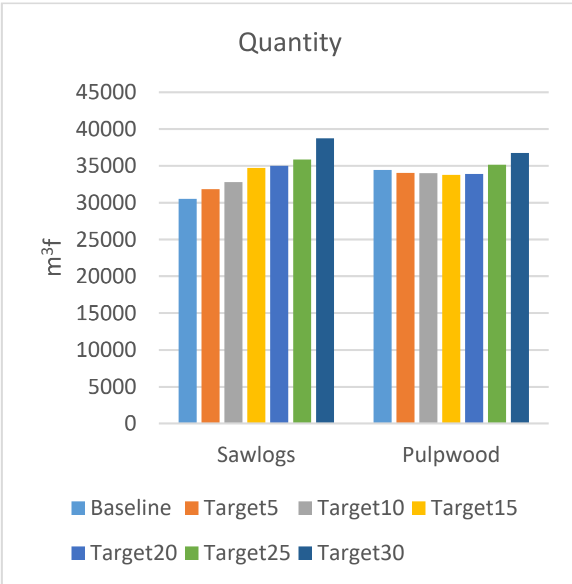

Figure 7: Harvest of sawlogs and pulpwood (spruce, pine and non conf. added together) in m^3f.

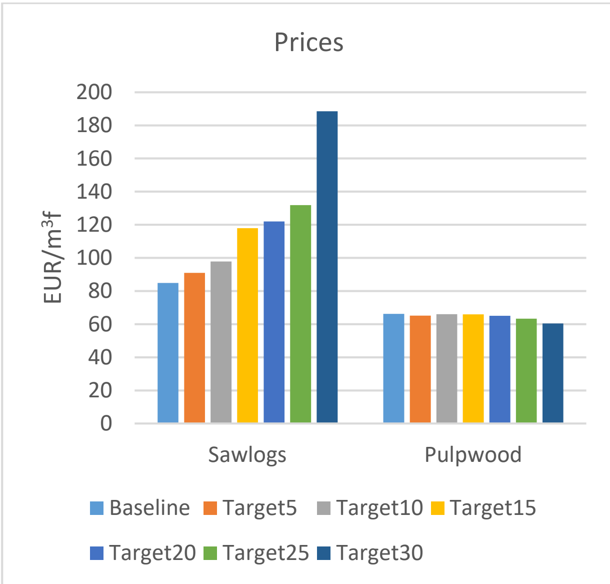

Figure 8: prices of sawlogs and pulpwood in EUR/m^3f.

Figure 9 shows that for 15 TWh of Bio-SNG production, the price of pulpwood falls below the price of wood chips. If pulpwood would have been allowed to be used as a feedstock in the HP sector, or in Bio-SNG production, a shift in the use of pulpwood would have been expected for high levels of Bio-SNG production. Thus, the waste hierarchy established by the EU is shown to be binding for 15 TWh of Bio-SNG production.

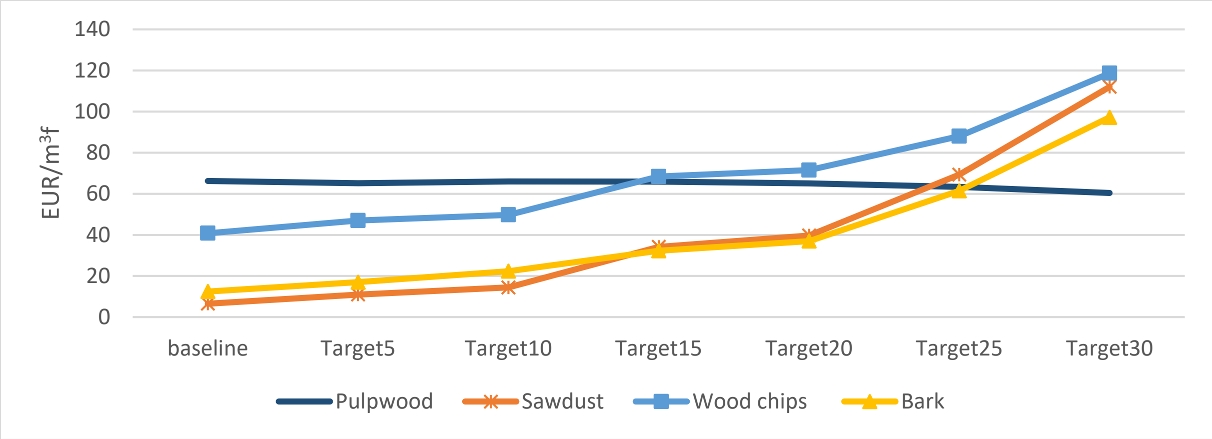

Figure 9: Price development of pulpwood and by-products (sawdust, wood chips and bark) m^3f.

To conclude, the prices of all by-products increase due to increased competition for the forest raw material, confirming that the HP sector becomes less profitable in the presence of increased 2G biofuel production. The competition for sawdust increases the most, and is re-allocated from the HP sector to Bio-SNG production. The HP sector is covering up the feedstock shortage with harvesting residues, something that is made possible due to increased roundwood harvest (the by-product effect). Moreover, the fiberboard and particleboard industry eventually shut down due to higher input prices (the competition effect). The exit of fiberboard and particleboard production leads to increased pulpwood exports.

4.2. Sensitivity analysis: the role of imports

The simulation results presented in the previous sub-section implied an increase in domestic roundwood harvest, equivalent to almost a sixth of Sweden's harvest levels in the year 2016. However, future import levels for Sweden are uncertain, and will be determined by comparative advantages in biofuel production, policies and exports. In this sub-section, imports are allowed to increase by 20% in relation to the levels observed in 2016. In this sensitivity analysis, we focus on the following feedstocks: forest industry by-products, pellets, sawlogs and pulpwood. The scenario results from section 4.1, i.e., assuming fixed imports levels corresponding to the 2016 levels, will be referred to as the "Base case". The scenario results in the sensitivity analysis, with an increased ceiling for possible import levels, are referred to as the "Higher import case". Several results from this analysis are worth emphasizing.

First, the feedstock composition in Bio-SNG production does not change significantly; the main feedstocks are still sawdust and pellets. However, a larger proportion of the feedstock is imported in the Higher import case. The full import ceilings for industry by-products and pellets are reached already after 15 TWh of Bio-SNG production. For instance, with 15 TWh of Bio-

SNG production, a total of 2.2 million m³f domestically harvested sawlogs and associated harvesting residues, are replaced by 2.4 million m³f of imported sawlogs. Since imported sawlogs generate no supply of harvesting residues (for use in the Swedish market), the imported amount of sawlogs has to be greater than the domestically amount of sawlogs that it replaces. Pulpwood imports, though, remain stable.

The by-product price developments in the Higher import case follow the same pattern as presented in the Base case. The price curve is shifted downwards, i.e., the increased imports delay the sharp price rises (see Figure 10). This is the expected result; the partial relaxation of the original constraint on imports provides the industrial actors with more flexibility in procuring feedstock.

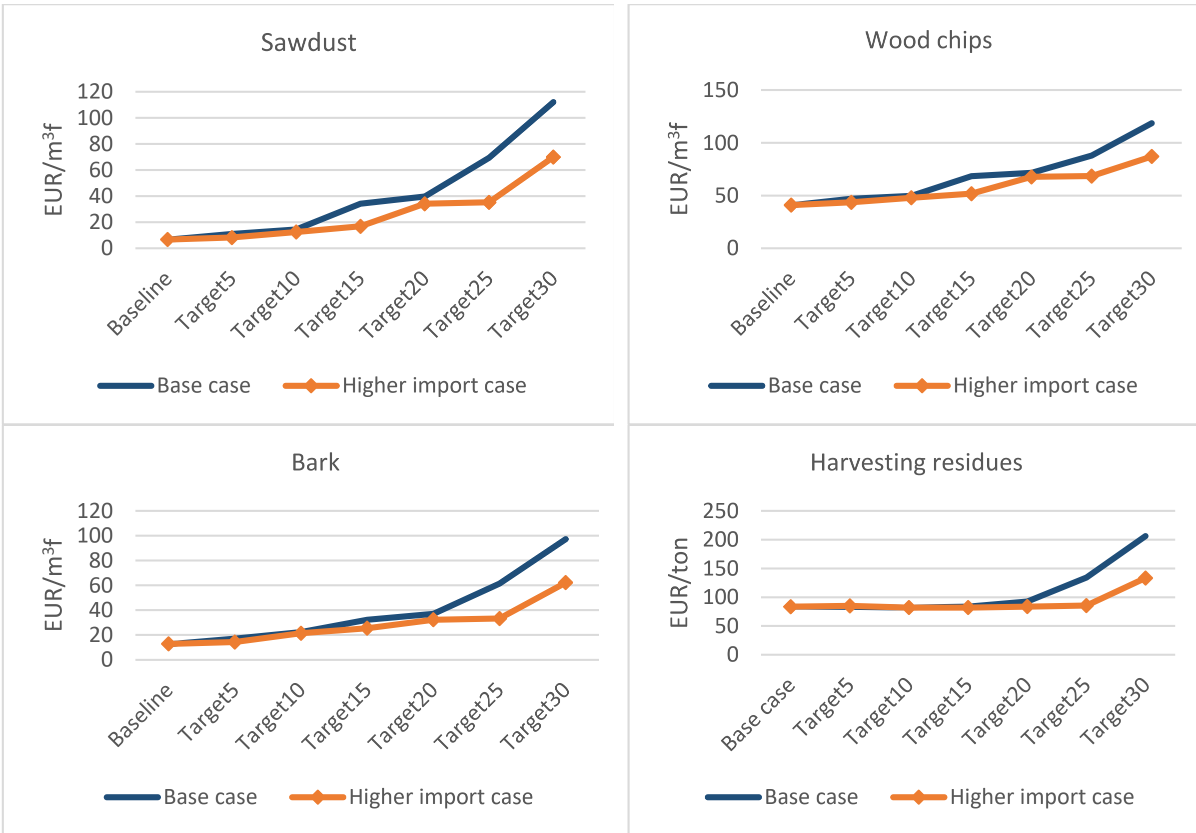

Figure 10: Price development for by-products and harvesting residues in the base case and in the Higher import case by-product is EUR/m³f and harvesting residues in ton (ODT).

The relatively lower by-product prices incentivize the HP sector to use more by-products, domestically produced as well as imported, and less of harvesting residues (see Figure 11). Figure 10 indicates that the price of harvesting residues also shifts downwards, similarly as in the case for the by-products. However, this change is not caused by an increased supply; supply is actually reduced due to decreased roundwood harvest. Instead, there is a decreased demand due to relatively cheaper industrial by-products.

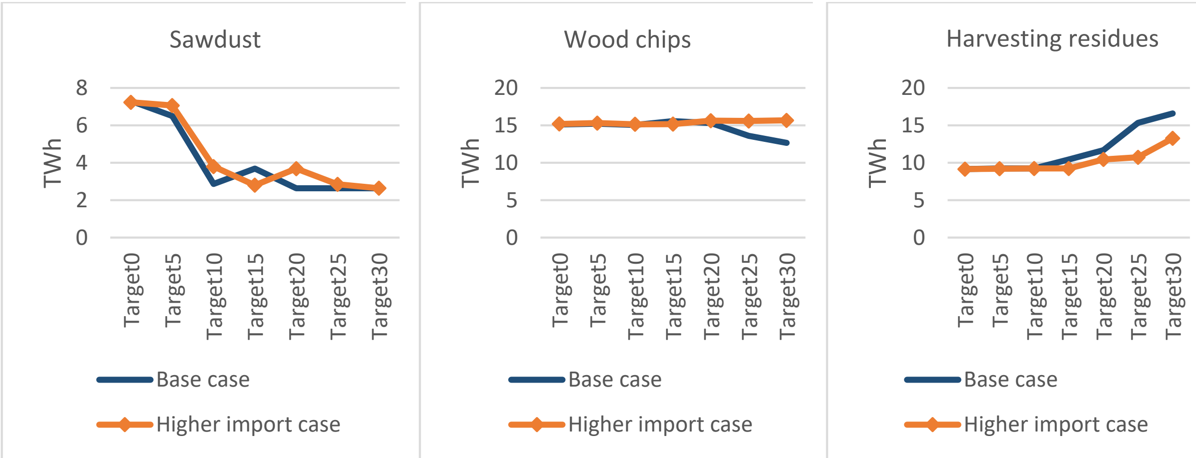

Figure 11 The use of sawdust, wood chips and harvesting residues in the HP energy sector (TWh).

The consequences of the increases in by-product prices in the Higher import case are also reflected in the forest industries' production levels (Figure 12).

Figure 12: Domestic forest industry production levels (in 1000 ton) for 0-30 TWh Bio-SNG under the Base case and the More import case.

The production of fiberboard and particleboard, respectively, decreases and eventually both industries shut down. However, in the Higher import case, this shutdown is delayed; it takes place only when the production of Bio-SNG reaches 20 TWh (compared to 15 TWh in the base case). The production levels for sawnwood and paper are relatively stable due to direct substitution of imported raw materials for domestically harvested sawlogs and pulpwood. Since the board industry survives longer in the Higher import scenario, the domestic demand for pulpwood remains positive for higher levels of Bio-SNG production. Thus, the increase in pulpwood exports is lost, and for this reason, pulpwood harvest is lower in the Higher import scenario.

To conclude, regardless of whether import levels remain at 2016 levels, or increase by 20%, the general production patterns in the Swedish forest raw materials market will remain fairly stable. Yet, a delay in events is expected; the increase in sawdust and harvesting residue prices are delayed, and so is the board industries' reduced production. Moreover, increased imports also lead to lower harvest of roundwood, and therefore also of harvesting residues.

5. Discussion and avenues for future research

This study demonstrates how feedstock competition in the Swedish forest biomass market can be affected when implementing various 2G biofuel demand targets. It also demonstrates the linkages between the HP sector and the forest industries; how these linkages can lead to both increased competition and industry shutdowns, but also to synergy effects in the markets for industry by-products. The simulated results are dependent on assumptions, such as which 2G biofuel technology is available, the available feedstocks, as well as model structure. This section provides a discussion of these issues, and introduces a few avenues for future research.

5.1. Competition and by-product effects

The competition and the by-product effects are generally not separable and quantifiable since they occur simultaneously. Yet, and as indicated above, the course of events can be discussed in the light of these effects. All feedstock prices increase in the investigated scenarios, and two fiberboard industries eventually shut down, thus suggesting that the 2G biofuel demand targets lead to increased competition for the forest raw material. At the same time, though, there is also evidence of synergy effects between the sawmill sector and the use of forest raw material in the HP sector. Higher by-product prices spur sawmills to produce more sawnwood, something that in turn makes forest owners increase their harvest levels. Already at the lowest level of Bio-SNG production, there is an increase in the harvest level, thus suggesting that the by-product effect kicks in from start. Moreover, in the scenario with the highest Bio-SNG production, the average sawnwood price increases by only less than a percentage due to increased returns on by-products.

In addition to forest industry by-products, harvesting residues use increases with more intense roundwood harvest activities, and this will have a mitigating effect on prices in the forest raw material market. More harvesting residues can be used in the HP sector, and this helps dampen some of the upward pressure on the price of industry by-products. This could in part explain the slowdown in the by-product price increase observed between 15 and 20 TWh of Bio-SNG production. The ups and downs in pellets and fossil fuel use, together with the increasing use of harvesting residues at 15 TWh of Bio-SNG production, suggest that the by-product effect tends to intensify at 15 TWh of Bio-SNG production. In the sensitivity analysis with increasing imports, the above by-product effects are however reduced due to a decrease in domestically supplied harvesting residues.

Moreover, since this study has shown that the prices of by-products (sawdust, wood chips and bark) do influence the behavior of sawmills; sawdust, wood chips and bark, the feedstocks may better be described as *co-products* than by-products in the sawmilling sector. Thus, in contrast to by-product demand, the demand for these feedstocks does influence the production decisions concerning the main product – in this case sawnwood.

5.2. Similar studies in other empirical contexts

The outcomes generated from a partial equilibrium model are dependent on parameters, such as modeling assumptions, inputs and outputs included, and choice of technologies (Khabarov and Obersteiner, 2018; Rafajlovic and Cardwell, 2013; Thompson et al., 2010; Whistance, 2012). Clearly, these factors will differ across various, using similar yet different models and in various empirical contexts.

Our results of benefitting sawmills and losing pulp mills are well in line with the findings by Trømborg et al. (2013), who also assess the market effects of introducing 2G biofuels production, but in Norway. However, Trømborg et al. (2013) find raw material prices to increase significantly more than what is found in this study. Specifically, their results suggest that in the presence of a 4.5 TWh[11] increase in 2G biofuel production, the price of roundwood (pine in their case) increases by over 60%. In the present study, however, a similar increase in 2G biofuel demand generates a corresponding price increase of only 5%. 2G biofuel production has to be at least 30 TWh, before a 60% increase in the price of pine can be observed. These differences do highlight the different prerequisites between countries in terms of existing production and resource endowments. For this reason, the feedstocks available to produce biofuel also differ between the models. Whereas our model incorporates by-products and harvesting residues, the model of Trømborg et al. (2013) defines pulpwood as the key feedstock, something that also explains the sharp price increase reported for roundwood. Thus, the choice of feedstocks clearly matters for the modeling outcomes. The same applies to the choice of technologies, which together with the feedstock constitutes the IO-coefficients. If, for instance, gasification of black liquor, an often underutilized by-product from the pulping industry, would be included as a 2G biofuel technology, and integrated with the pulp and paper sector, this industry would be a potential winner (Zetterholm et al., 2018).

5.3. Assumption concerning the outtake of harvesting residues

The quantities of feedstock available in the forest raw materials market are crucial for the price formation of feedstocks, and in the model, for which levels of 2G biofuels that will affect other sectors. Quantities of roundwood harvest and forest industry by-products bought and sold in the market are monitored by forest agencies and/or self-reported by industries, and made available as public data. However, public data exist neither for potential harvest, nor actual harvest, of harvesting residues. For this reason, researchers have to rely on techno-economic estimations and approximations. The supply of harvesting residues is constrained by the level of roundwood harvest. However, the potential harvest of residues after felling is debated; in order to ensure environmental sustainability (avoid erosion, biodiversity losses etc.), some of the residues have to remain on the ground. De Jong et al. (2017) argue that an increase in the outtake of harvesting residues by 2.5 times current levels could be sustainable. However, others fear environmental backlashes for any harvest of residues on site since left-over biomass on the ground is important for the forest's biodiversity to recover after felling (e.g. Toivanen et al., 2012). Porso et al. (2018) show that an increased pellets production using harvesting residues leads to carbon stock changes in soil and biomass, and this contributes to global warming.

[11] These authors do not specify which biofuel that is produced in the model. Assuming a biofuel for which one (1) liter is equal to 32.5 megajoule, 500 million liters biofuel equals 4.5 TWh.

However, if coal in power plants can be replaced with pellets made from harvesting residues, an increased use of harvesting residues could instead contribute to mitigated climate change (Porso et al., 2018). Thus, there is no consensus on the optimal harvesting residues outtake level. Nevertheless, the assumed harvesting residues levels are likely to affect the modeling outcomes for high levels of 2G biofuel production (when by-product prices approaches the price of harvesting residues per MWh produced 2G biofuel).

The amount of available harvesting residues in the model is obtained from estimations by Carlsson (2011), which in turn build on techno-economic estimations of harvesting residue potentials. Recalling Figure 4, the price of harvesting residues becomes lower compared to forest industry by-products at 15 TWh of Bio-SNG production. With lower or higher harvesting residues outtake, the prices could be higher respectively lower, and thus the intersection of relative prices at a different level of Bio-SNG production.

5.4. Avenues for future research and model developments

Even though this paper has revealed some important results, more research is called for in order to provide a more comprehensive picture of the market impacts from introducing 2G biofuels. In addition to model developments of the market model itself, the market model could be soft-linked to other models in order to address a wider range of aspects related to the market impacts from introducing 2G biofuels.

First, adding a time dimension to the model would enable analyses of endogenous technological learning, feedstock price and resource allocation development over time, as well as various developments in energy efficiency and electrification of the transport fleet. The time aspect is an important economic factor – according to Mustapha et al. (2017a) technological learning following the increased penetration of 2G biofuel production could outweigh the initial price increases.

Secondly, more technologies in the model would open up for the use of other feedstocks in 2G biofuel production, e.g., black liquor from the pulp- and paper industry. This way, more nuance would be added to the analysis regarding future winning and losing industries. Opening up to additional feedstock ranges (e.g., sawdust 50-100% and wood chips 50-100%) in the sets of IO-coefficients (for technology and feedstock), could capture the various industries' substitution possibilities between feedstocks more accurately. This would in fact be similar to the model

GLOBIOM's treatment of feedstock substitution in biodiesel production (Hugo Valin et al., 2013).

Thirdly, in order to analyze the spatial price dimension, the model could be soft-linked to techno-economic models (e.g. Pettersson et al. (2015). For instance, by linking to a spatially explicit localization model, the geographic price aspects and the integration of biorefinery technologies with existing forest industries, would be better incorporated in the analysis. By applying an iterative approach, feedstock price dynamics caused by biorefinery capacity enlargement can also be analyzed, as described by Bryngemark et al. (2018). Furthermore, the market model could be soft-linked to a model simulating environmental impacts. This could provide insights to whether an intensified harvest of harvesting residues would lead to more or less roundwood harvest given the forest raw material price developments, while considering the environmental impacts (e.g. via feedstock composition in the HP sector and forests carbon sequestration) of doing so.

Finally, the scenarios investigated in this study could be implemented in a different numerical model with the same data to compare the modeling approaches and perhaps different outcomes. Such comparisons would contribute to a deeper understanding of the various models' driving forces as well as pros and cons for addressing specific research questions. A model to compare with could be a Constant Elasticity Model (CES), which would provide another way to deal with feedstock substitution. The CES model treats feedstock substitution explicitly and allows for continuous substitution (in contrast to indirect substitution in discrete steps).

6. Conclusions

The aim of this study was to analyze the price and resource allocation effects in the HP sector and forest industries from introducing domestic 2G biofuel production in Sweden. Six scenarios involving 5-30 TWh of Bio-SNG production were investigated. For this purpose, the national forest sector model SFSTMII model was extended with a module including 2G biofuel production, and then applied with data for the year 2016.

All by-product prices increased due to increased competition for the forest raw materials, confirming that the HP sector becomes less profitable in the presence of increased 2G biofuel production. The competition for sawdust increased the most, and was re-allocated from the HP sector to Bio-SNG production. The HP sector was covering up the feedstock shortage with harvesting residues, something that was made possible due to increased roundwood harvest (the by-product effect). Already at the lowest level of Bio-SNG production, there was an increase in the roundwood harvest level, thus suggesting that the by-product effect kicked in from start.

Moreover, in the highest Bio-SNG production scenario, the average sawnwood price increased by only less than one percentage due to increased returns on by-products. With an additional roundwood harvest equaling a less than a fifth of 2016 harvest levels, a third of the Swedish road transport fuel demand could be satisfied with 2G biofuels produced from forest industry's by-products. In the case in which by-products and roundwood harvest imports could increase up to 20% in addition to 2016's imports levels, domestic harvest would have to increase by a little less than a tenth. However, if imports increase, less harvesting residues would be supplied and the competition for by-products would increase. Due to increased feedstock prices, the fiberboard and particleboard industry eventually shut down (the competition effect). The exits of fiberboard and particleboard production lead to increased pulpwood exports.

At a general level, this paper has highlighted the importance of considering price formation in forest biomass markets when developing bioenergy and 2G biofuel policies. Depending on the policy design, synergies may be achieved as well as increased competition for raw material leading to industrial shutdowns. While the model presented in this paper offers a good starting point for analyzing the impact of 2G biofuel demand targets on a national forest raw material market, considering techno-economic and environmental aspects provide an important subject for future research. One possible solution would be to soft-link SFSTMII to a modeling framework considering aspects such as the optimal location of 2G biofuel production.

Acknowledgments

The work has been carried out under the auspices of Forskarskola Energisystem, financed by the Swedish Energy Agency. Economic support from the Swedish Research Council Formas is also gratefully acknowledged. The author thanks Patrik Söderholm and Elisabeth Wetterlund at Luleå University of Technology, and Nicklas Forsell, Anu Korosuoa and Pekka Lauri at the International Institute for Applied Systems Analysis, who all provided insight and expertise that greatly assisted the research.

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Appendix

Million m^3f	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp	Wood chips	Sawdust
Region1	0	0	0	0,82	0,65	0,06	0	0
Region2	0	0	0	0,73	0,44	0,06	0	0
Region3	0	0	0	0,49	0,38	0,04	0	0
Region4	0	0	0,02	1,38	0,47	0	0	0
ROW	0	6,19	7,37	14,88	14,19	-10,00	94	115

Table A1: Exogenous roundwood supply added to the data due to material imbalances in the calibration procedure. Column 2-4 show exogenous supply for sawlogs (spruce, pine and non-coniferous), and column 5-7 for pulpwood (spruce, pine and non-coniferous).

Paper III

sustainability

MDPI

Concept paper

Techno-economic market evaluations of biorefinery concepts: an interdisciplinary framework

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Abstract: Biofuels and biochemicals are likely to play significant roles in achieving the transition towards a fossil free society. However, large-scale biorefineries are not yet cost-competitive with their fossil-fuel counterparts, and it is important to identify biorefinery concepts with high economic performance in order to achieve widespread deployment in the future. For evaluation of early-stage biorefinery concepts, there is a need to consider not only the technical performance and the process costs, but also the performance of the full supply chain and the impact of its implementation in the feedstock and products markets. This article presents a conceptual interdisciplinary framework that can constitute the foundation for future evaluations of the full supply-chain performance of various biorefinery concepts. This analytical framework considers the competition for biomass feedstocks across sectors, and assumes exogenous end-use product demand and a number of geographical and technical constraints. It can be used to evaluate the impacts of the introduction of various biorefinery concepts in the biomass markets in terms of feedstock allocations and prices. Policy evaluations, taking into account both engineering constraints and market mechanisms, should also be possible.

Keywords: Biorefinery; biomass; techno-economic evaluation; partial equilibrium model; market analysis; process integration; supply chain optimization; interdisciplinary framework

1. Introduction

Lignocellulosic biorefineries producing biofuels and biochemicals are likely to play a significant role in achieving the transition towards a fossil-free society, especially in forest rich countries such as Sweden, Finland and Canada [1,2]. Since biomass is a limited resource, it is important to optimize the environmental and economic efficiency of biorefineries [3]. Furthermore, large-scale biorefineries are not yet cost-competitive with their fossil-fuel counterparts, and early-phase evaluation is therefore needed to identify low-cost biorefinery concepts. A biorefinery is analogous to a petroleum refinery, but with biomass as the feedstock. A variety of design variables affects the economic performance of a biorefinery, e.g., the choice of conversion technology, localization, feedstock, and final product(s). These aspects are often included in assessments conducted using supply chain optimization models, see e.g., [4,5]. Such models can be used to identify biorefinery concepts, i.e. a specific combination of feedstock, conversion technology, final product(s), and optimal location, which minimizes the system costs for a given set of constraints (e.g., available feedstock, plant capacity, etc.). Typically, transport costs are here endogenously determined whereas biomass-to-product yields and feedstock prices are included as static input data (i.e., determined exogenously).

Even though all the central decision variables are considered in the supply chain model, the modeling output may be misleading since it does not acknowledge the dynamics of feedstock prices. The implementation of large-scale biorefineries will influence feedstock prices due to an increased demand for the specific feedstocks used in the process. Furthermore, the price signal from increased competition for a given feedstock will induce a re-allocation of feedstocks in the biomass market, thus generating a complex price formulation for the feedstocks included in the model. In other words, the feedstock price assumed in the supply chain evaluation model may no longer be valid as soon as the concept is assumed to enter the market. Implementation of a solution that has identified, for instance, sawmill chips to be used as feedstock at a cost of 11 EUR/MWh, may increase demand for this specific feedstock, thereby increasing the equilibrium market price to, say, 14 EUR/MWh, a level at which the biorefinery may no longer be profitable. Such price interactions with other sectors are typically not included in supply chain studies even though biomass feedstock costs generally constitute a large fraction of a product's total costs; see for instance [6] for an extensive review of techno-economic studies evaluating lignocellulosic ethanol for transport fuel use. These authors warn of misleading results: "cheap and largely available feedstock may often not be a reality" [6]. One explanation for the hesitation of combining techno-economic and market aspects is the obstacles associated with combining two different modeling approaches. Previous research has highlighted that to fully assess the future performance of emerging technologies, the system that these will be implemented in needs to be considered [7]. One approach is to use scenario-based analyses where consistent assumptions regarding the surrounding system are employed [8]. However, including assumptions regarding the market will not capture the impact of a biorefinery on the feedstock markets since the interaction between sectors are not considered.

In this article, we propose a conceptual interdisciplinary modeling framework for evaluating biorefinery concepts, considering both techno-economic aspects as well as endogenously determined feedstock prices, and thus the competition for raw materials. It has been shown that integration of biorefinery concepts with host industries for the utilization of waste heat and products can increase the economic performance of the production plant [3,9]. Integration with traditional forest industries are of particular interest since such plants usually have biomass-derived by-products from their main processes, as well as significant experience in operating large-scale biomass supply chains. Therefore, the proposed methodology considers the possibility for the biorefinery to be co-located at an existing industrial site, including the need to describe the integration synergy gains in an appropriate manner.

Figure 1 provides a general overview of the conceptual modeling framework and the directions of data between three generic models; a process evaluation model (left), a supply chain model in the (middle), and a market model (right). The supply chain model provides techno-economic data to the market model, which in turn provides market based feedstock price data back to the supply chain model and to the process evaluation model. Based on this new data are generated and used as input in the market model. This conceptual modeling framework can be used to evaluate, for instance, new biorefinery products integrated with existing forestry industries on site. Profitability can be assessed by testing different combinations of technologies and biomass feedstocks in an iterative process, as well as price changes in the forest and bioenergy sectors.

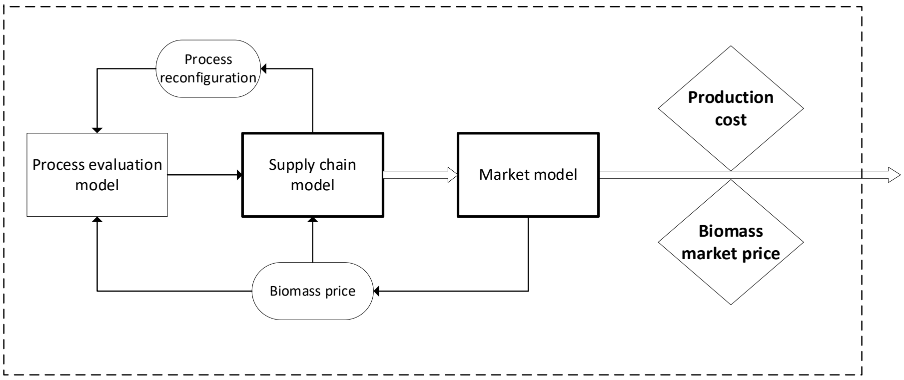

Figure 1. Overall modeling framework

The remainder of the paper will be organized as follows: the first part identifies key aspects for evaluating biorefinery concepts building on previous studies (Section 2). The second part presents the conceptual framework describing how these aspects may be combined for modeling purposes (Section 3). Finally, a concluding discussion is provided (Section 4).

2. Evaluating biorefinery concepts

This section provides an introduction to the main perspectives used for evaluating the economic performance of a biorefinery concept. These perspectives include: the detailed process evaluation for identifying integration benefits, the biomass-to-product yields and process costs, the supply chain optimization for evaluating low-cost system performance localizations and configurations, and the economic market modelling for identifying the biomass market impacts in terms of prices and the possible substitution of feedstock in other industries.

2.1. Techno-economic aspects

The full system performance of a biorefinery concept depends on several decisions regarding the supply chain configuration, from the supply side concerning the raw biomass feedstock to the finished product. This work differentiates between the methods needed to determine the plant level performance, which relates to the choices of equipment and process parameters at each site, and the supply chain performance, which includes plant level performance but also decisions concerning, for instance, harvesting site, modes of transport, and localization of the biorefinery facilities.

2.1.1. Plant level

A biorefinery generally includes biomass handling and pre-treatment units, e.g. drying and/or chipping and a main processing unit, e.g. gasifier, or fast pyrolysis reactor, where the feedstock is decomposed into different chemical components. The processing unit is followed by the cleaning and upgrading units where unwanted products (e.g., tars) are removed, and the remaining components are converted to the desired end-products. The performance of the biorefinery will depend on the equipment and the chosen operating parameters, and it is necessary to determine the biomass-to-product yield and the plant's energy and mass balance. It is also important to apprehend the plant investment cost for each considered production technology, as well as the integration opportunities.

To assess the biomass-to-product yield, energy efficiency and production cost, techno-economic evaluations are needed, see e.g. [10–12]. These studies typically investigate and/or optimize the cost of production of a biorefinery process in a bottom-up model with detailed descriptions of process equipment and material and energy flows. The system boundaries of these studies are often limited to the process, thus ignoring both the supply-chain perspective and any biomass feedstock market impacts. This excludes, e.g., emissions and costs related to emissions, and feedstock re-allocation and the relative price changes that arise as a result of altered feedstock demand.

The methods used for modeling the plant-level performance of a biorefinery are dependent on the specific technology and the technical state of the biorefinery concept. The modeling of existing processes, or processes that have been thoroughly researched, is mainly a subject of mimicking existing results. For *ex ante* assessments of new biorefinery concepts, modeling is, however, a more complex issue. Several methods for the modeling of thermochemical conversion of biomass have been suggested, see e.g. [13–15]. For processes with robust experimental data, a bottom-up, statistical approach can be used to validate a process model to identify the mass- and energy balances of various processes [16].

For process types where the detail level of the available experimental data is not sufficient for statistical evaluations, simulation models accounting for reaction kinetics or thermodynamic restrictions can be used to simulate the processing unit, see e.g. [11,14]. Using kinetic data can give satisfactory results for limited reactions, but the modeling of all physical and chemical interactions are currently too complex. In addition, thermodynamic or restricted thermodynamic models can be introduced in flowsheet simulation software, but this type of approach is generally characterized by substantial deviations from experimental results. Nonetheless, such approaches have been common in gasification modeling, mainly due to a lack of better alternatives.

The process model can be used to estimate the process costs. The process costs comprise two parts; the capital costs and the operating costs. The capital costs include the cost of each process unit, but also the indirect costs, such as the costs for start-up, contingency and installation. To relate the investment costs to the fuel production rate, the investment costs are annualized using a capital recovery factor (CRF), which combines information about the interest rate and the economic life-time of the investment. Investment costs do not scale linearly with scale of production; the investment costs per produced quantity of fuel decline with increasing process scale, i.e., indicating economies of scale. To estimate the investment costs, an investment cost function is used, and this relates to how each specific process is designed. The operating costs of the process include the costs for feedstock, utilities, operation and maintenance (O&M), and revenues from process by-products.

2.1.2. Supply chain aspects

The economic performance of a biorefinery concept will often be significantly influenced by the localization. For the plant level evaluations, these are in most cases done for a specific localization considering the characteristics of that specific site. However, the local characteristics can vary across different sites, e.g., in terms of feedstock availability, regional characteristics, modes of transport, localization of potential host industries for integration and their specific characteristics, and the prevalence of competing users of biomass, which can impact the total supply chain costs [17–19]. These variables in large part affect the biomass transport cost of the biorefinery supply chain, and these costs will depending on the supply chain configuration constitute a significant part of the total costs [20,21]. It is therefore important to include the decision variables affecting the biomass transport cost when evaluating the total biorefinery supply chain costs. The configuration of the supply chain considering these decision variables is often analyzed in supply chain optimization models. These models can include a variety of components in their analysis, e.g., supply chain design, planning and operation, technology selection, as well as different environmental sustainability assessments [19]. The purpose is to capture larger parts of the costs, and emissions that occur for a biorefinery concept and that are not addressed in the plant-level techno-economic evaluation.

The supply chain optimization models investigating the facility localization problem have most commonly been implemented as mixed integer linear problems (MILP), where binaries can be used to represent facility establishment in different capacities, and the continuous variables represent the material flows in the studied system [22]. The MILP implementation is suitable both due to the possibility to represent large-scale problems, and because it can be used to describe a large number of variations of the supply chain problem, including e.g. social and environmental objectives [23], and strategic, tactical and operational perspectives of the biorefinery supply chain [24,25]. However, they require a large number of decision variables to describe complex problems and can require long computational times [23,26]. The MILP problems also have difficulties in incorporating supply chain uncertainties, such as demand fluctuations, biomass supply, and prices [25]. Furthermore, due to the linear nature of the model, it faces problems with non-linear behavior such as the costs for increasing the production capacity (economies of scale). This can however be mitigated, e.g., by using discreet capacity steps as inputs to the model. Alternatively, the facility capacities can be determined outside the optimization procedure.

When using a supply chain model that includes not only the potential localization, but also the industries that are competing for the same feedstock, it is possible to capture the changes in costs for transportation in the entire studied system, when implementing biorefineries [27]. Generally, these models rely on plant level evaluations to determine the biomass-to-product yield and the investment costs (or investment cost function), which are used as exogenous input data. Such studies typically minimize total system cost to identify viable biorefinery concepts for a specific region or plant.

2.2. *Market aspects*

A biomass market includes raw materials, by-products and intermediate products. Raw materials are energy crops, roundwood, etc. Typical by-products in the forest industry sector include bark, sawdust and shavings. By-products can be further processed into intermediate products that can be sold on the biomass markets, such as pellets produced from sawdust supplied to the bioenergy sector. The price formation of raw-materials is dependent of the total supply of raw-material (i.e., available quantities, extraction/harvesting costs etc.) and the demand-led competition for the raw materials. A by-product on the other hand does not have a cost per se since it is a spillover product, although in reality there is often a cost for basic management of the material, yet a price will occur for the product whenever there is a market demand for it. Since the by-product supply is constrained by the main production levels, the quantity supplied will not increase independently in the presence of increasing demand; supply is therefore characterized by an inelastic supply responses meaning that the price will increase more than the increase in demand [28]. If the price of the by-product increases to the point where profitability is higher for the by-product than the main-product, the producer may adjust its production to make the by-product the main (or a co-)product, meaning that the production levels are no longer constrained to the production level of the main product. The disappearance of the initial main product production is likely to affect feedstock prices, and in turn the composition of feedstocks in other industries and sectors.

This article focuses on lignocellulosic biorefinery concepts, something which makes the forest biomass market an interesting example. Sweden will be used as an example of a national forest biomass market to illustrate the flows of biomass flows that determine the feedstock prices. The market characteristics described here will be represented in the partial equilibrium market model presented in Section 3.2.[1] In principle, a CGE model could be used for our purposes, but this could also increase the complexity of the analysis. Obviously, one important benefit of CGE model is that they provide a consistent description of how all sectors of the economy interact (e.g., following changes in relative prices, etc.), however arguable at the expense of detailed descriptions of key sectors of interest. The types of market model that we propose is in fact a combination of CGE and partial equilibrium modeling in that it describes the interaction between several markets, not the least various energy markets and the markets for forest raw materials, but does not describe all feedback mechanisms in the overall economy.

In the context of the Swedish forest biomass feedstock market, price formation will be heavily dependent on whether the demand for one material will affect another sector's demand for the material via the price signals, and less affected by total supply of raw material quantities [28]. The

[1] The term *market model* is chosen to describe models based on neoclassical economic theory. The reason for not solely using the term *economic model* is to avoid confusion with the so-called techno economic models.

forest industry sector and the bioenergy sector compete for forest raw materials. The forestry industry is also a (direct) supplier of industry by-products, and an (indirect) supplier of harvesting residues, which can be used as input in the bioenergy sector. Saw logs and pulp wood go to the forest sector that produces, e.g., paper, sawn wood, and board. The forest industry also produces by-products, such as sawdust, which can be used as input in the particle board production on site, or supplied to other users through the by-product market. By-product streams (sawdust etc.) flow from the forestry industry to the energy conversion sector as well as the intermediate industries producing briquettes and pellets from by-products, used in the bioenergy sector. Raw biomass is supplied to the bioenergy sector, either as roundwood or harvesting residues, very much depending on the availability and cost considerations.

The following example illustrates the price mechanisms in the forestry biomass market. Forest owners supply sawn wood to saw mills and pulpwood to the pulp- and paper industry (PPI). Still, if the bioenergy sector faces feedstock prices (by-products, harvesting residues etc.) equal to the price of roundwood, and wants to increase output, pulpwood may be chipped and used in the bioenergy sector. A possible scenario could be: increased price for pulpwood (via increased competition and/or increased imports of this feedstock) reduces PPI production. The industry becomes less competitive and may exit the market in the long-run; this would in turn have considerable price and allocation effects in the biomass market. Furthermore, black liquor is a by-product from pulp manufacturing, and it is today used for the PPI's internal heat production, but has been identified in several studies to have a significant potential as feedstock for producing renewable fuels in the transport sector (see e.g. [29]) – a possibility which would disappear with the domestic PPI industry's disappearance.

Thus, the price formation in the biomass market is a complex issue where the competition for raw materials as well as the supply of and demand for by-products are central components. In order to analyze changes in a given market considering this complex web of demand and supply among sectors, it is necessary to adopt an economic model that captures the market behavior of the sectors (flows of feedstock based on price signals) defined through demand and supply functions for each sector. To analyze potential market effects from introducing policy instruments, partial equilibrium (PE) models are often used, see e.g. [30–35]. These models typically focus on a restricted part of the economy, e.g. the flows of biomass between the forestry industry sector and the bioenergy sector, and they therefore leave many other variables out. This allows for the use of disaggregated data, which in turn permit analyses of, for instance, the price effects of restricting a specific type of pellets used in the energy sector in a given region.

In studies focusing less on the biomass market and more on the national effects of biofuel policies, general equilibrium models (CGE) are often used (e.g. [36,37]). For a very recent review of CGE modeling studies assessing the income-generating consequences of implementing biofuel policies, see [38]. Both in PE and CGE modeling, market behavior is described through supply and demand functions with some defined behavioral parameters (e.g., price elasticities). By maximizing social welfare (i.e., the sum of producer and consumer surplus) under certain restrictions (e.g. raw material supply), endogenous feedstock prices are generated. In both modeling approaches, forest industry production, bioenergy conversion and biofuel production are typically modeled by activity analysis where input–output (IO) coefficients define the inputs used to produce one unit of output, see e.g. [33]. The fixed structure can in turn be motivated due to the fixed technological infrastructure in the short run [39]. A PE model can contain many IO coefficients for many combinations of feedstocks and end-use products, and even for different geographical locations. A CGE model can contain many national IO coefficients. The possibility to disaggregate the feedstock market makes the PE-approach suitable for market evaluations of new technologies. However, a market model (PE or CGE) will primarily address the price and quantity impacts of fixed, pre-defined technologies.

2.3. Integrated assessment

2.3.1. Previous literature and the scope of this article

A general need for interdisciplinary approaches in order to better support energy policy decision-making has been emphasized; see for instance [40,41] both of which attempt to combine an economic model with an energy system model in order to better understand how energy policies affect the national economy. It has also been emphasized that there is a need for interdisciplinary approaches to fully assess the performance of different biorefinery concepts, including integration, technological components, and economic, environmental, and social aspects [42]. There is a significant body of knowledge related to biomass-to-product yield estimations, supply chain evaluations, and biomass feedstock markets. However, to the best of the authors' knowledge, no studies combine knowledge from all three domains into a coherent analytical framework to evaluate biorefinery concepts.

Still, there is a general trend in the literature to integrate environmental aspects to assess supply chain efficiency. In addition to identifying the least cost options, sustainability is treated as a key parameter [43]. The majority of previous integrated studies consider either the techno-economic or environmental (life cycle) aspects of bioenergy projects, see for example [44,45]. Greenhouse gas (GHG) emissions are one of the most frequently used environmental indicators, production and capital costs are the preferred economic measures, and the number of created jobs is the most considered social criterion [43]. These three aspects have been studied simultaneously for the supply chain configuration of biofuel production [46]. However, the price dynamics of the biomass are generally not considered.

One biochemical production study included several levels of production performance including; metabolism, bioreactor, overall process, chemical industry, economy, and ecosystem [47]. However, the supply chain configuration with respect to localization was disregarded even though this could significantly influence the economic performance of the full supply chain performance. Another way to include more aspects into one study is to consider so-called multi-objective optimization, see for instance [48] where a supply chain is optimized for economic profits, minimizing environmental impacts, and maximizing job creation. Still, this approach also neglects the impacts of biorefinery production on price formation in the feedstock markets.

There are numerous techno-economic and market-focused studies that analyze the competition for feedstock caused by first-generation biofuel production. Land-use and global market effects are central here.[2] See, for instance, [49], which identified that crop yields differ among regions, and that in order to provide accurate estimates of the land use and market effects, regional feedstock demand has to be estimated. The market effects were then assessed in a regional market model (in this case a global static partial equilibrium model), where the estimated regional demand from the localization model was included as additional exogenous demand to the model [49]. This study constitutes an interesting example of how to gain modeling accuracy by using the output from one model as input in another model, although it does not include an iterative process.

Since feedstock prices constitute a large share of the total costs of a biorefinery concept, ignoring price formation in supply chain analyses as a consequence of introducing the concept may result in misleading conclusions concerning the profitability and efficiency of that same concept. In order to capture the true cost of a biorefinery concept, there is therefore a need to not only to consider the cost of the technology, but also changes in feedstock prices and demand caused by the introduction of the biorefinery. This is not often done and an explanation for that are the obstacles that emerge when combining different research traditions and methods; models in techno-economic studies differ from market models in terms of modeling structure, optimization, scope of disaggregation, among others.

[2] The aspects related to indirect land use are central in the context of first generation biofuels as such fuels are made from sugars and vegetable oils found in arable crops, which in turn make biofuels to compete with food production. Second generation biofuels are however produced from lignocellulosic biomass such as harvesting residues, agricultural residues or waste, and do not therefore compete for arable land.

Figure 2 illustrates the objective of this article, i.e., to decrease the gap between techno-economic and market modeling in order to provide a conceptual holistic modeling framework for biorefinery concepts. The left part of Figure 1 shows the current relationship between the three aspects discussed. Supply chain models commonly treat biorefinery performance and configuration as static parameters in the evaluations. However, modeling frameworks have been developed integrating both process design and supply chain management in e.g. [50], here illustrated with a small purple-green overlap. Some market analysis studies include techno-economic aspects e.g. [49] as well as techno-economic studies that include market conditions see e.g. [51], but leave out price formation, illustrated with a small purple-red overlap between the market model and the supply chain model. The right part of Figure 2 illustrates the objective of this paper: an illustration of a framework where techno-economic aspects and feedstock market aspects are considered in a more integrated approach.

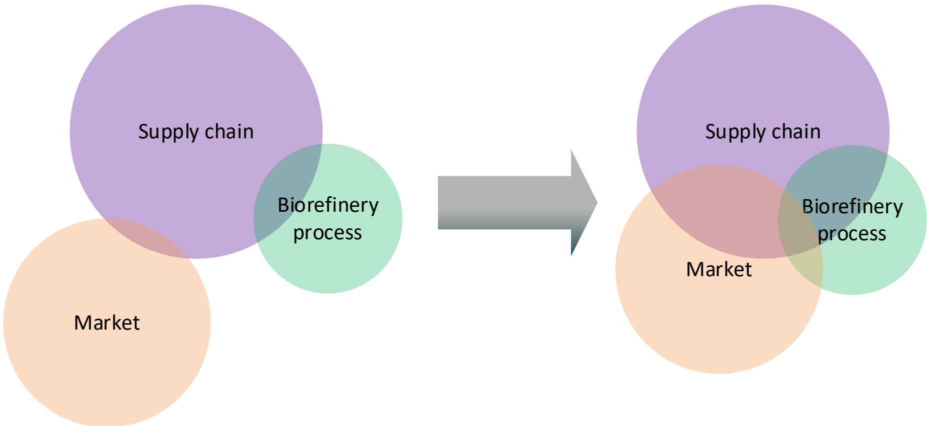

Figure 2. Towards a more integrated modeling framework: illustration of the contribution of the paper.

2.3.2. Model-linking

Essentially, there are two main pathways for combining different systems perspective models: hard-linking and soft-linking. When using hard-linking, system levels are modeled within the same modeling framework, i.e., one model with one objective function. There are several obstacles related to this approach out of which the most apparent is the need to formulate a single objective function without losing the specific modeling features for different system levels.[3] Additional drawbacks include the lack of model transparency when the model grows larger, and hardware limitations for running a model comprising large quantities of data. To include the process modeling within the same framework as the supply chain and the market model, is essentially not possible with today's computers. It is likely that the market level and supply chain level could be modeled within the same framework, but in order to do that there is a need to reduce the complexity of the sub-models (see also Bauer et al., 2008). In a soft-linking approach, the models are optimized/solved separately and data are exchanged between the models. In order to retain the models' complexity, soft-linking is often preferable [53]. Furthermore, soft-linking provides flexibility regarding the choice of models to be included in the framework, and has been shown to work successfully for linking of CGE (market based) models with energy system models (a type of techno-economic model) [40,41].

As noted above, a biorefinery has many decision variables and several of these can be broken down into disaggregated models in order to increase the accuracy of the results. Furthermore, added models can easily be removed in favor of another model, all depending on the research question of interest. For the soft-linking to work, the added model and the model with which it will exchange information only need to share one input and output variable. This variable will work as the data exchange channel between the two models. Comparing this to hard-linking where the models share a common objective function, which adds much more requirements on data similarities and similar modeling structures, soft-linking seems to be the natural choice for an interdisciplinary framework.

[3] Multi-objective optimization is of course possible, but will lead to an amplification of the other two obstacles.

3. Modeling Framework

As feedstock prices constitute a considerable part of the total production costs of a biorefinery, these prices affect the outcome in product yield as well as supply chain evaluations. Our framework brings together a techno-economic approach and a market approach into one modeling framework in order to evaluate various biorefinery concepts in the presence of endogenous feedstock price formation. To illustrate a few key theoretical aspects in techno-economic evaluations and market evolutions, three schematic modeling approaches are presented. The specific choice of model can be adjusted for other applications of the framework. This paper exemplifies the iteration of models with different modeling structures and objective functions. The modeling framework presented focuses on the evaluation of lignocellulosic thermochemical biorefineries, but with the use of a similar approach it should be possible to evaluate other biorefinery routes as well. Moreover, for illustration purposes, Sweden is used as an example in the proposed modeling framework, but any country or area can be investigated using the framework. The framework is constructed so that three key performance indicator (KPIs) categories are easily obtained from empirical applications of the framework. These are: (i) new biomass feedstock prices [e.g., in EUR/MWh], (ii) new biomass feedstock allocation among sectors and industries, (iii) and costs of biorefinery products produced in the solution [EUR/kWh]. The KPIs are chosen so as to provide a quick insight into the market effects related to implementing biorefinery concepts, as well as to gain information regarding the prices of the end-use products of interest. Moreover, the KPIs may be exchanged depending on the purpose of the application.

3.1. Techno-economic performance

The techno-economic system performance of the biorefinery concept is determined by a mixture of plant level and supply chain modeling, while accounting for the changes in the biomass feedstock prices from the market model. To identify the full techno-economic performance, the plant level process configuration has to be evaluated. This is needed to determine the investment cost, biomass-to-product yield, and surplus or deficit of heat or electricity. Depending on the technology-specific biorefinery technology and the current technical state of the process equipment, different methods are required to represent the process units. With satisfactory representation of the processing units, pinch analysis can be applied, partly to establish heat recovery targets, thus estimating the minimum net energy added to the process, but also to identify possible process integration opportunities with host industries [54]. International Energy Agency (IEA) defines process integration as "systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and environmental effects," [55]. For the techno-economic evaluation we suggest to include a modeling concept where the biorefinery can exchange heat with any given host industry. Integration of a biorefinery plant with a host industry results in a concept where the combined primary energy usage is lower compared to stand-alone concepts. Some types of biorefineries may have a total heat surplus that is large enough to produce excess electricity through a steam cycle. The aim is to identify the full supply chain cost for producing the desired biorefinery product, here exemplified as biofuel, while considering both plant level and supply chain design decisions, e.g. feedstock choice, integration decisions, size of facility, localization and host industry.

Figure 3 displays a generic process model evaluating biomass-to-product yields for biorefinery products, integrated with a given host industry (e.g. a sawmill, a refinery or a chemical cluster). The input of the model is biomass feedstock composition and moisture content, as well as process unit operating parameters, such as reactor temperatures and pressures. The model quantifies the energy and mass balances of the plant; this is in turn required to calculate the net heat and electricity generated/required by the process and the overall biomass-to-product yield. Generally, host industries are not modeled separately, mainly since these industries already exist and thus are not subject to design. Instead, process stream data or generalized research models of different process types are applied to capture process integration opportunities. Typical processes suitable for process integration include: pulp and paper mills, sawmills, petrochemical industries and refineries. District heating networks could also be suitable as hosts for new biorefineries.

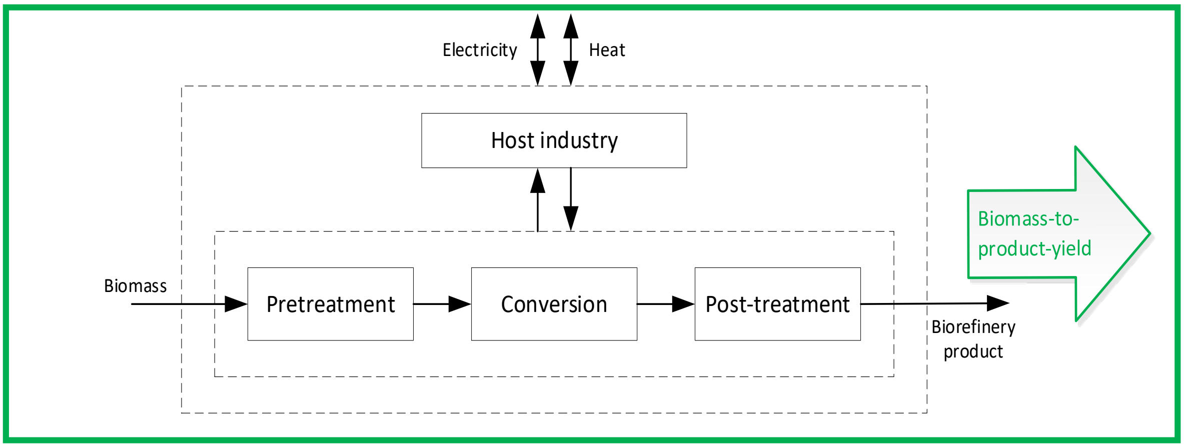

Figure 3. Overview of the system boundaries for techno-economic evaluation of a generic, host-integrated, thermo-chemical biorefinery.

The output from the plant-level process model include biomass conversion yield, i.e., the quantity of biorefinery products produced per quantity of biomass input, together with net energy input/output in terms of electricity and heat. The electricity, heat and conversion yield, together with the capital cost function and the running costs of the process constitute input data to the market and supply chain models, respectively.

The full system performance of a biorefinery concept can then be determined in a supply chain optimization model, which also considers the transport network, the changes in transportation for other industries due to the biomass feedstock demand of the biorefinery. A geographically explicit MILP model for analysis of localization of biorefineries is suggested, due to the necessity for a model to be able to consider many potential localizations as well as the plant configuration (including capacities) are determined in the process evaluation model. The model includes spatial data for e.g. feedstock availability, as well as localization of host and competing industries, with description of the internal energy flows and demands of potential host sites for biorefinery integration [27]. The system performance can thus be determined considering various geographical restrictions, not only due to feedstock availability, but also due to restrictions in the integration opportunities. Figure 4 presents a schematic overview of inputs and outputs of the model.

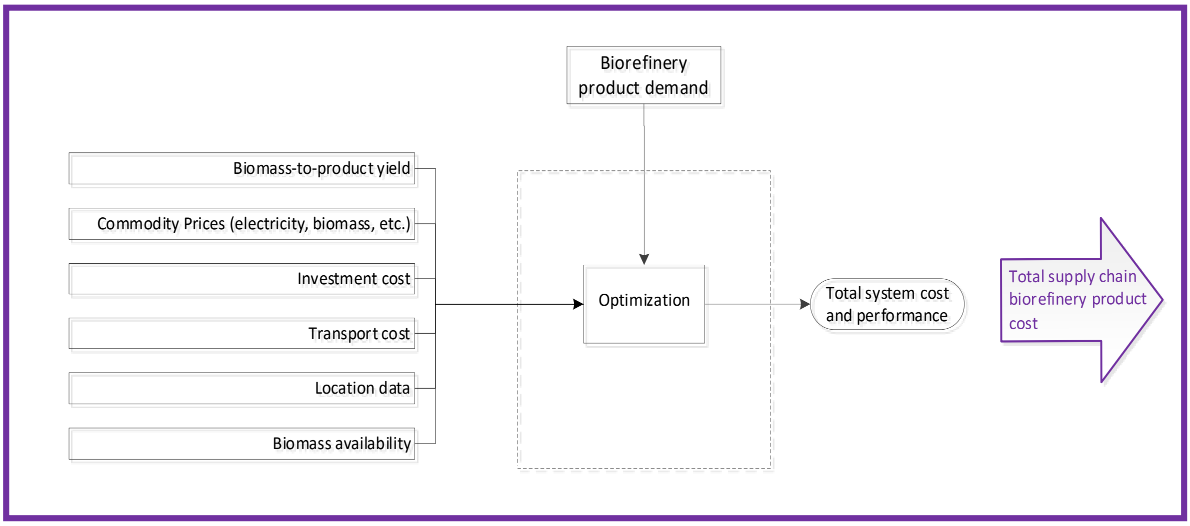

Figure 4. Main input and output data for supply chain optimization modeling approach

All data represented in boxes to the left in Figure 4 are exogenous parameters in the model. The end-use product demand is the exogenously determined driver of the model. It determines the products to be produced and how much of each of these. Demand may in turn be determined based on, for instance, policy objectives or predicted market demand. Given the demand, the supply chain optimization model will configure the lowest cost supply chain configuration, and in this way the performance cost of various biorefinery concepts can be determined. Depending on the study, a multi- or single-technology problem can be investigated and the lowest cost solution could result in one or more biorefineries needed to satisfy the product demand.

The total system costs include all supply chain costs described in the model, e.g., transport costs, feedstock costs, technology costs, etc. The total transport cost is endogenously determined in the supply chain model depending on modes of transportation and transport distances. Biomass is disaggregated into the same categories as used in the market model, e.g. pulpwood, saw logs, forest residues, and stumps, and their respective prices are exogenously defined. The electricity market is exogenously treated and viewed as a fixed demand market, i.e. excess or deficit electricity at the biorefinery plant level is assumed to be resolved by purchasing or selling electricity at a given price.

The output from the model is the lowest cost biorefinery localization(s) and technology/ies. Based on the output, the system performance for each biorefinery site can be determined. The performance costs include capital and operational costs, costs for transportation (also considering eventual impact on transport of biomass for other purposes), biomass feedstock costs, and the costs or revenues from deficit or surplus electricity. The performance costs for the biorefinery/ies are used as inputs to the market model. Given that the supply chain model provides information on each specific geographic localization, the model results are aggregated for biorefinery technology and type of host industry for the use in the market model, e.g., gasification integrated with CHP (combined heat and power) plants or fast pyrolysis integrated with sawmills.

3.2. The market model– feedstock allocation and prices

The contribution of the market model in this integrated framework is to allow for endogenous price formation of biomass feedstock considering market competition for materials. Key output variables in the market model are: biomass feedstock allocation and prices, biorefinery product prices and production levels. For our purposes, a national generic PE model describing the Swedish forestry sectors and the Swedish bioenergy sector, respectively, is used to investigate price formation in the forest biomass feedstock market. The reason for choosing a partial equilibrium model is that it allows for disaggregated data; this is desirable in the context of the forest biomass markets with many products and actors. The modeling structure used in this work is similar to several previous PE forest sector models see e.g. [56,57]. It is a microeconomic model focusing one country's forest biomass market. Demand for end use products and energy is exogenous, whereas production, conversion and demand and supply of intermediate products are endogenously determined.

International trade is represented by trade with one external region (rest of the world), and serves as a competitor to the domestic regions. Figure 5 illustrates the main actors and biomass flows in the model. Supply of raw wood material and demand for energy and forestry end-use products are exogenously determined, shown as the upper box and the lower box, respectively, in Figure 5. The forest industries and the bioenergy sector demand raw materials. The forest industries also supply by-products to the bioenergy sector (as discussed in Section 2.2). The middle box with dashed lines shows the interconnection between the forestry industry and the bioenergy conversion sector. The small boxes inside this box represent the industries and bioenergy conversion activities (represented by I-O coefficients). Maximizing social welfare (producer and consumer surplus) leads to an optimal allocation of feedstock given the various demand and supply constraints which generate endogenous feedstock prices.

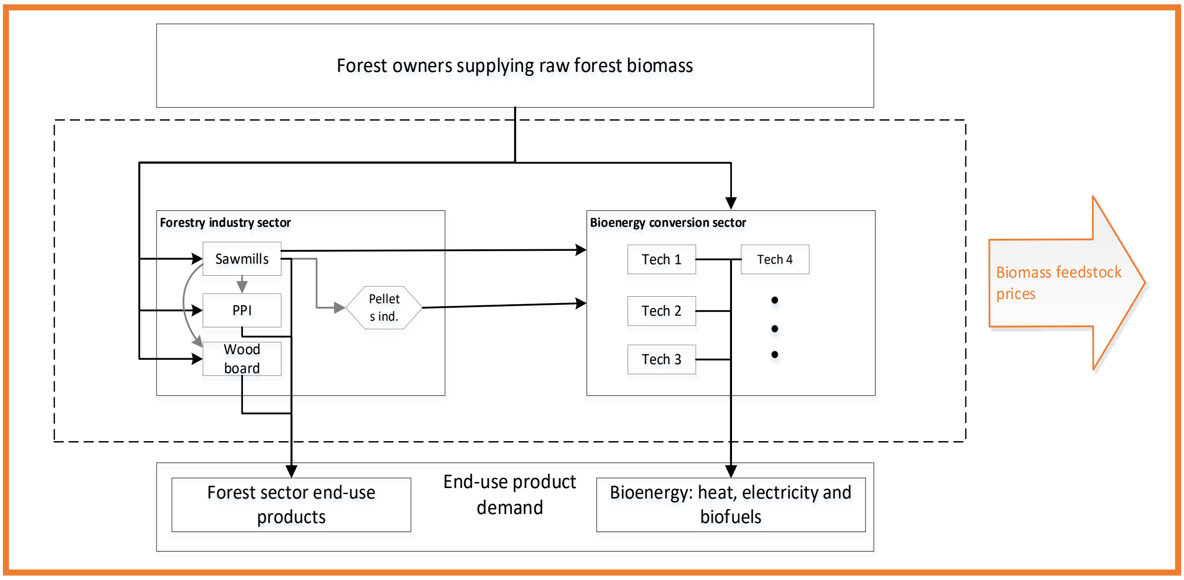

Figure 5. Schematic illustration of the forest raw material market model

Finally, by maximizing consumer and producer surpluses, exogenous demand will drive the model to choose the least cost supply option for production, and market feedstock prices will be determined accordingly. These results can then be fed into the supply chain model. For a policy scenario in which, for instance, 50% of all transportation fuels have to come from forest biofuels, the market model will choose the least cost option to produce forestry and energy products given this constraint. This will lead to a reallocation of feedstock, and will therefore also affect feedstock prices.

3.3. *Integrated assesment: the iteration process*

Whereas the shrinking distances between the circles in Figure 2 illustrates the objective of this article; to decrease the gap between techno-economic and market modeling in order to provide a holistic modeling framework for biorefinery concepts, Figure 6 shows how this can be done hands-on in an iterative modeling framework. Figure 6 shows the suggested linking process between the evaluation model, the supply chain model, and the market model. The iterative process can be used to evaluate biorefinery concepts using techno-economic evaluations. It considers the change in feedstock prices as a consequence of introducing the biorefinery concept to the market.

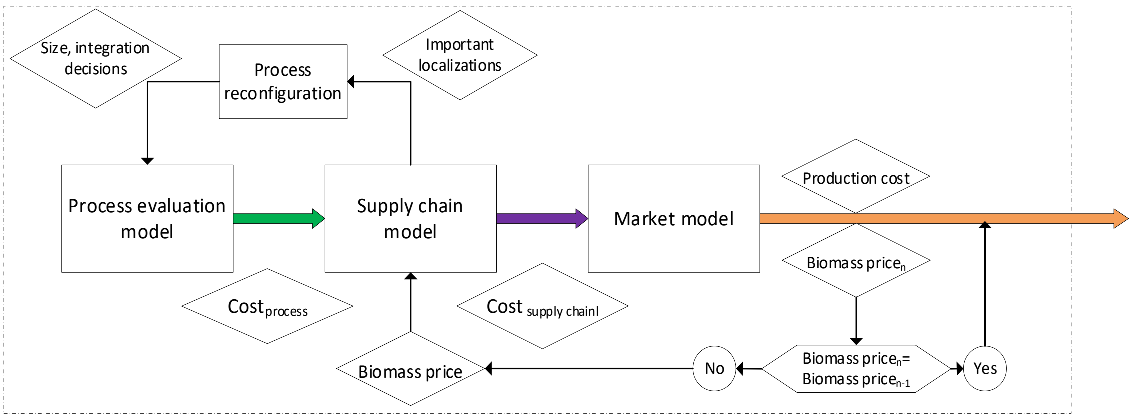

Figure 6. Iteration procedure of the modeling framework

The separate sub-models in the framework have different modeling structures including different aggregation levels of the data. Therefore, some data need to be adjusted prior to iteration. In such cases, the supply chain model includes plant-specific data (and generates plant-specific output data), whereas the market model is aggregated on sectors and large geographical regions. One solution is to adjust the output data from the supply chain model before entering the market model as follows: each biorefinery technology and integration option is specified with a cost for conversion rather than localization. By creating a single cost for conversion for each process technology and industry *type*, rather than for each process technology and specific industry *localization*, some discrepancy between the technology representations in the supply chain and market model will appear. However, using this approach, the specific site characteristics are implicitly included in the market model.

The flows of data can proceed in line with the following process (see Figure 6).[4] The process yield, electricity and heat production/demand are the main physical output data from the process modeling. Together with the process integration opportunities and process costs, they constitute the input variables to the supply chain model. Using feedstock prices from the market model, the model will identify the lowest cost technology mix to satisfy the demand for the specified biorefinery product. The feedstock price determined through the market model constitutes new input data to the supply chain model through an iterative feedback loop. The new feedstock price influences the performance cost for the different technology options in the supply chain model, which might in turn influence the lowest-cost supply chain configuration. If the new cost-minimizing supply chain differs from the previous solution, the resulting biorefinery technology choices and localizations constitute inputs to the process model through a second feedback loop. In this ways, the process models can be updated and re-run for integration with different types of industrial host sites which might affect the output of electricity and/or district heating.

The new results from the process models again constitute input to the supply chain model, and the latter will generate an updated performance cost. These new results provide updated feedstock requirements, and cost data to the market model that in turn generate new feedstock prices and biomass allocation in competing sectors. For each iteration *N*, the new biomass price produced in the market model is compared to the biomass price generated in the previous iteration *N-1*. When the price of iteration *N* equals the price from iteration *N*-1, the solution has converged. The biomass price and biorefinery product prices of the last iteration are the final and resulting output price data.

Theoretically, the price data iterated between the models will eventually converge. However, given the structure of the framework, with separate models interconnected through soft linking, there is a possibility that convergence issues can emerge. If the supply chain model responds to the changes of price data with drastic changes in supply chain configurations, the model solutions might diverge. If this problem arises, it can be dealt with by applying an under-relaxation factor, meaning that the changes in output price from the market model between the model runs is manually decreased. i.e. if the feedstock price increases a lot between two iterations, the feedback to the supply chain model are lowered from the actual supply produced from the market model.

4. Concluding discussion and Avenues for Future Research

This paper has attempted to bridge the gap between techno-economic and market modeling in order to evaluate new biorefinery concepts. Two techno-economic aspects and one market perspective were presented followed by a novel conceptual modeling framework exemplified with three soft-linked models: a biorefinery process evaluation model, a supply chain evaluation model and a market model. The market model includes the bioenergy sector and the forestry industry sector, and captures the price dynamics of biomass feedstocks. Although a partial equilibrium model is used to illustrate the market effects, the soft-linking procedure would be similar if relying on a CGE model. The important difference to be made is between market modeling (endogenous prices), and the techno-economic models (i.e., exogenous prices). The supply chain evaluation model considers geographical aspects and technological options for bio-refineries, and the process evaluation model considers detailed description of the plant-level material and energy flows. The combination of the models

[4] A more detailed overview with specific examples of the data exchange between the system aspects is provided in Appendix A.

provides an opportunity for a holistic early-phase evaluations of various biorefinery concepts, i.e., considering both technical and geographical aspects, and the price dynamics of biomass feedstock with other sectors demanding forest biomass. In a future application, the schematic approaches will be complemented with specific models including detailed representation, e.g., choice of functional forms of demand and supply. Such work is currently ongoing in the empirical context of Swedish biorefinery development. Moreover, we also envisage that the framework should stimulate modeling applications in other contexts by other researchers.

As previously stated, evaluating the potential for a biorefinery concept using only a techno-economic model may result in misleading conclusion regarding the production cost as the production cost is heavily based on feedstock prices, which in techno-economic models are static across demand levels [6]. As described in Section 2.2, when demand increases for one feedstock, e.g., due to the implementation of a new biorefinery concept, the price of the feedstock will initially increase. Still, the final price effect is not straightforward as the price is formed in the market where the price change affects feedstock allocation and production levels in the affected industries and sectors. Applying the framework developed in this paper provides supply chain analyses that are robust to feedstock price changes that arise as a consequence of introducing the biorefinery concept to the market.

Forest sector modeling has been used successfully to analyze exogenous shifts at the biomass markets, such as the introduction of a new bioenergy production technology [58]. Yet, whereas these studies are limited to assess price and feedstock allocation as a consequence of an exogenous shift, this framework also ensures the technology to be chosen as to minimize the supply cost of the end-use product in terms of e.g. biomass-to-yield and transport costs. The technological flexibility needed in order to identify new efficient biorefinery concepts occurs in the iteration with the supply chain model. Indeed, the choice of technology implemented in a market model may be chosen based on supply chain studies ensuring the supply cost to be minimized without being part in modeling framework. So why bother with an iterative framework? The benefit is the iteration of information between the model that generates one stable solution considering all the decision variables included. The cost-minimizing choice of technology is dependent on feedstock prices. The feedstock prices are in turn dependent on the technologies included. Thus, optimal technologies included in a market model may not be optimal when feedstock prices have adjusted to the new production patterns. This framework ensures that the technologies included in the market model are chosen as to minimize total supply cost also when the feedstock price changes. A biorefinery has many decision variables, ignoring some of the key aspects is likely to result in misleading conclusions, with the risk of sending out conflicting policy recommendations.

The barriers associated with linking models from different traditions of research is a real obstacle –as not only do the models differ in terms of structure and objective function, also do the researchers representing the fields have different agendas. The use of soft-linking (in contrast to hard-linking) enables models to be brought together representing different aspects of a topic, while keeping the integrity of the models intact. The proposed framework is an example of how to soft-link models from the techno-economic tradition with the models in economics built upon market behavior. This framework can assist decision-makers in selecting cost-effective policies as the risk for goal conflicts is reduced.

The paper has focused on lignocellulosic thermochemical biorefineries, but through a similar approach it should be possible to evaluate other biorefinery routes as well. Similarly, Sweden was used in the modeling framework but any country or area can be investigated using the same framework. The modeling framework resulted in three key performance indicator categories (KPI's) of the biorefinery concept evaluated: (i) biomass feedstock prices [EUR/MWh], (ii) biomass feedstock allocation among sectors and industries, and (iii) price of biorefinery products produced in the solution [EUR/kWh]. In addition, the KPIs may be adjusted to suit the research of interest, although the procedure of identifying information-sharing channels would then have to be done.

Regarding future developments of this framework, it should be noted that so far it has been developed to improve the economic assessment of biorefinery concepts. However, as the political interest in new biorefinery concepts lies in the possibility of replacing fossil-fuel products with climate smart products, such as biofuels and green chemicals, and thereby decrease the pressure on the environment, additional decision variables are various environmental measures, e.g. greenhouse gas emissions (GHG), air quality etc. The GHG emissions related to the biorefinery supply chain should be easy to include by attributing the different flows with corresponding emissions

To further increase the accuracy of the economic assessment, the framework may also be soft-linked with other national models covering other countries (biomass markets) in order to simulate trade effects as a consequence of changing feedstock prices. A more sophisticated trade analysis would also provide insights regarding the exporting possibilities for a product produced in a specific biorefinery concept. A sophisticated trade analysis can also contribute to an environmental assessment. Another possible enhancement of the framework is to include the dimension of time – in the supply chain model for investment assessments, and in the market model to allow for gradual adaption of new technology and price changes. Gradual price changes may imply temporary feedstock allocation changes that generate chain effects which results in an end-point different to the end-point in a static analysis.

Lignocellulosic biorefineries producing biofuels and biochemicals have the potential to play a significant role in achieving the transition towards a fossil-free society, especially in forest rich countries such as Sweden [1,2]. In order to properly evaluating and comparing different biorefinery concept, modeling tools are needed. To draw conclusions and provide policy recommendations, holistic modeling frameworks including both the techno-economic aspects and the market aspects are needed.

Acknowledgments: The work has been carried out under the auspices of Forskarskola Energisystem financed by the Swedish Energy Agency. Economic support from the Swedish Research Council Formas is also gratefully acknowledged (Grant 254-2013-100), as well as from Bio4Energy, a strategic research environment appointed by the Swedish government. We thank Patrik Söderholm, Elisabeth Wetterlund and Simon Harvey, who provided insight and expertise that greatly assisted the research.

Author Contributions: Elina Bryngemark contributed with the market modeling aspects, Jonas Zetterholm contributed with the supply chain aspects, and Johan Ahlström contributed with the plant-level process aspects.

Conflicts of Interest: The authors declare no conflict of interest

Appendix A

Figure A1 presents a more detailed overview exemplifying the data linking the three different system level approaches. The detailed descriptions of these flows are described in Table A1. Green boxes and arrows correspond to external input data and output data from the process evaluation model, purple boxes and arrows corresponds to external input to and output data from the supply chain model, while red boxes and arrows corresponds to external input and output data from the market model. White boxes represent input data that are fed to several models, and pink boxes are input data that can be used for sensitivity analysis but that do not have to be included to run the model. The white boxes with blue lining represents the main output results from the multi-level framework.

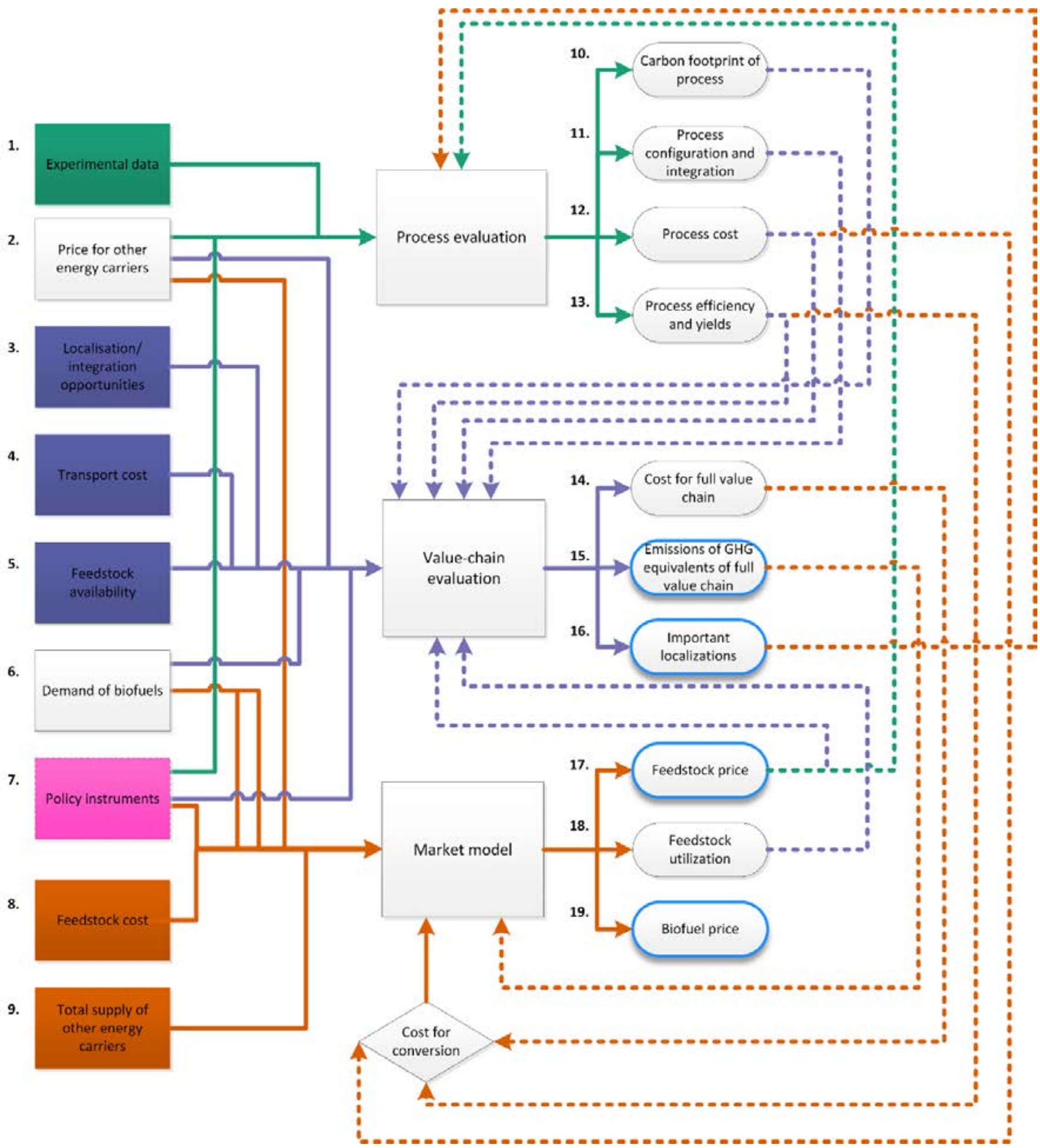

Figure A1. Description of a multi-perspective framework.

Table A1: Description of the data exchange between the different system models.

Number	Description	Unit
Input data		
1.	Experimental process data	°C, kg/s, biomass compositions, product gas compositions etc.
2.	Prices of all included energy carriers, e.g. electricity, steam, different types of biomass	EUR/MWh
3.	Localization and heat/feedstock integration opportunities	Longitude & latitude, $MW_{electricity}/MW_{biomass\ input}$, $MW_{district\ heating}/MW_{biomass\ input}$
4.	Cost of feedstock and product distribution	EUR/km
5.	Availability of feedstock	MWh/grid node
6.	Total demand of bio refinery products	MWh/year
7.	Optional input of policy instruments, e.g. CO_2 tax or feed in tariffs	E.g. EUR/kg_{CO2} or $EUR/\ MWh_{bioraff\ prod.}$
8.	Feedstock cost	EUR/MWh
9.	Total supply of energy carriers	MWh/year
Generated data		
10	The process design	-
11.	Process cost	Biorefinery product/$MWh_{biomass}$, Electricity/$MWh_{biomass}$, District heating/$MWh_{biomass}$
12.	Process efficiency and yields	-
13.	Supply chain cost	$EUR/MWh_{fuel\ product}$
14.	Environmental performance of supply chain	GHG equivalents/ $MWh_{fuel\ product}$
15.	Locations of importance and relevance for potential biorefineries	Characteristics of low cost localizations
16.	Prices on all different types of included feedstocks	EUR/MWh
17.	The demand of all types of included feedstock types	MWh/year
18.	Price of biorefinery product	$EUR/MWh_{bioraff\ prod,}$

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Department of Business Administration, Technology and Social Sciences
Division of Economics

ISSN 1402-1757
ISBN 978-91-7790-298-0 (print)
ISBN 978-91-7790-299-7 (pdf)

Luleå University of Technology 2019

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